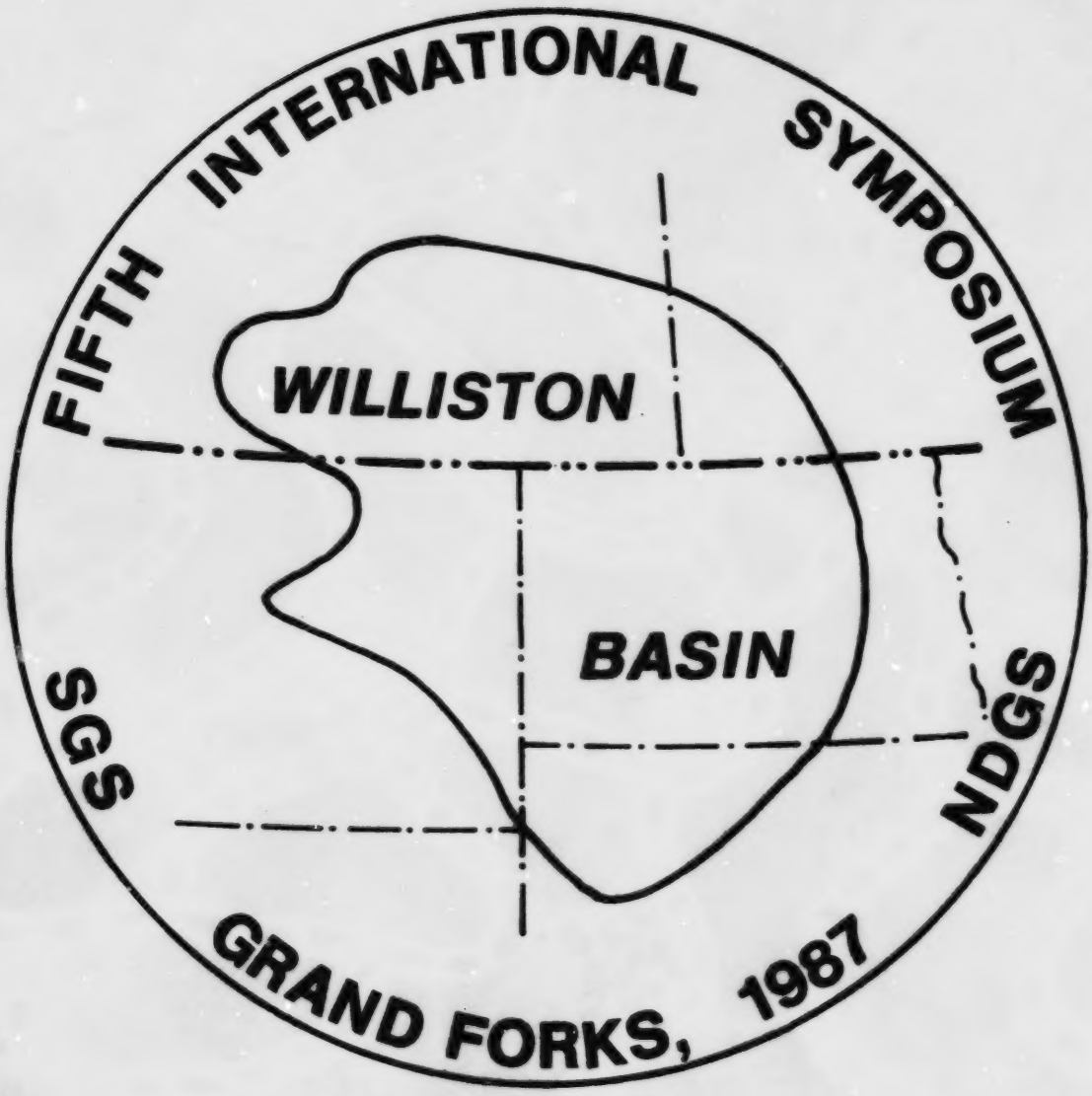


Edited by C.G. Carlson and J.E. Christopher

Special Publication Number 9

FIFTH INTERNATIONAL WILLISTON BASIN SYMPOSIUM

EDITORS:
C.G. CARLSON and J.E. CHRISTOPHER

Proceedings of a Symposium
Held in Grand Forks, North Dakota
14, 15, 16 and 17 June 1987

Sponsored by:
North Dakota Geological Society
Saskatchewan Geological Society

SPECIAL PUBLICATION NUMBER 9
SASKATCHEWAN GEOLOGICAL SOCIETY
P..O. BOX 234
REGINA, SASKATCHEWAN
S4P 2Z6 CANADA

1987

COVER:

Catenipora (Halysites) gracilis Chain coral

Red River Formation (Ordovician), Manitoba

Magnification ×3

Specimen and cover design: D.F. Paterson

Canadian Cataloguing in Publication Data

International Williston Basin Symposium (5th : 1987 : Grand Forks, N.D.)
Fifth International Williston Basin Symposium

(Special publication / Saskatchewan Geological Society ; no. 9)

Includes bibliographical references.
ISBN 0-921547-16-1 (bound) - ISBN 0-921547-17-X (pbk.)

1. Geology—Williston Basin — Congresses. I. Carlson, C.G. (Clarence Gustav). II. Christopher, J.E. (James Ellis). III. North Dakota Geological Society. IV. Saskatchewan Geological Society. V. Title. VI. Series: Special publication (Saskatchewan Geological Society) ; no. 9.

QE79.157 1987 557.84 C87-098059-9

ISBN 0-921547-17-X
Copyright © 1987
Publisher:
Saskatchewan Geological Society
P.O. Box 234, Regina, Saskatchewan, Canada S4P 2Z6

Type-setting:
TypeWest (1985) Inc.
605a Park Street, Regina, Saskatchewan, Canada S4N 5N1

Printing and binding:
Midwest Litho
P.O. Box 1466, Saskatoon, Saskatchewan, Canada S7K 3P7

PRINTED IN CANADA
—EDUCATIONAL MATERIAL—

TABLE OF CONTENTS

Symposium Committee v
Editorial Committee v
Society Executives, 1987 vi
Foreword vii
Saskatchewan Geological Society Corporate Members, Sponsors and Donors, 1987 viii

General Papers

New oil from old ideas: an historical review of wildcatting in "Frontier Saskatchewan" ..... S.P. Halabura 1
Factors determining the thermal history of a continental basin ..... W.D. Gosnold, Jr. and Y.C. Huang 17

Stratigraphic Papers

Earliest Paleozoic history of the Williston Basin in North Dakota ..... R.D. LeFever, S.C. Thompson and D.B. Anderson 22
The Winnipegosis Formation of the northeastern margin of the Williston Basin ..... L.R. Rosenthal 37
Distinguishing between depositional and dissolution thinning : Devonian Prairie Formation, Williston Basin, North America ..... C.A. Oglesby 47
Macrofossils and stratigraphic subdivisions of the Bakken Formation (Devonian-Mississippian), Williston Basin, North Dakota ..... L.C. Thrasher 53
Summary of the biostratigraphy of the Bakken Formation (Devonian and Mississippian) in the Williston Basin, North Dakota ..... F.D. Holland, Jr., M.D. Hayes, L.C. Thrasher and T.P. Huber ... 68
The Madison, a nomenclatural review with a look to the future ..... C.G. Carlson and J.A. LeFever 77
Corals from the Madison Group, Williston Basin, North Dakota ..... D.L. Waters and W.J. Sando 83
Waulsortian-type mounds in the Mississippian of the Williston Basin : new interpretation from old cores ..... R.D. Sereda and D.M. Kent 98
Environmental significance of a megaspore flora from the Mission Canyon Formation (Mississippian), Bottineau Country, North Dakota ..... M.R. Luther, E.N. Steadman and L.V. Hills 107
Cyclicity in the Mission Canyon and lower Charles Formations of the central Williston Basin ..... J.L. Hoff 117
Depositional cycles in the Mississippian Mission Canyon Limestone and Charles Formation Williston Basin, North Dakota ..... D.L. Waters and W.J. Sando 123
A reconnaissance sedimentological study of the Middle Jurassic Upper Shaunavon Formation, southwestern Saskatchewan ..... R.C.L. Wilson 134

Structural Papers

Structural evolution of the central and southern portions of the Nesson Anticline, North Dakota	J.A. LeFever, R.D. LeFever and S.B. Anderson	147
Salt dissolution and tectonics, south-central Saskatchewan	G.J. McTavish and L.W. Vigrass	157
Structural history of Poplar Dome and the dissolution of Charles Formation salt, Roosevelt Country, Montana	D.M. Orchard	169
Tableland photolineament pattern revisited	J.D. Mollard	178
Late Cenozoic erosion of Williston Basin sediments	E.N. Clausen	190

Oil Habitat Papers

A geologic and economic appraisal of the oil potential of the Williston Basin (abstract)	A.H. Jennings	196
Geology of the Indian Hill Field area, central Williston Basin, North Dakota — a multiple-pay field developed in the 1980s	J.D. Mayer	197
Using capillary pressure techniques to map and identify an economic fairway in the Ordovician Red River on the western flank of the Williston Basin	J.B. Jennings	212
Hydrodynamic trapping in Mission Canyon reservoirs : Elkhorn Ranch Field, North Dakota	W.D. DeMis	217
Habitat of Sherwood oil, Renville County, North Dakota	M.L. Hendricks, B.P. Birge, Jr. and J.D. Eisel	226
Knutson Field and its relationship to the Mission Canyon oil play, south-central Williston Basin	R.W. Bogle and W.B. Hansen	242
Families of oils in southeastern Saskatchewan	P.W. Brooks, L.R. Snowdon and K.G. Osadetz	253

Abstracts

A stratigraphic test of gypsum dehydration and implications for basin development	C.K.L. Roark and T.E. Jordan	265
Salinity, oxygenation, and topographic controls on Mississippian subtidal sedimentation in a portion of the Mission Canyon Formation, Williston Basin, North Dakota	H.J. Fischer, M. R. Luther, K.E. Eylands and C.F. Quinn	266
Sedimentary and diagenetic controls on reservoir properties : Midale Field, southeastern Saskatchewan	J. Kaldi	268

SYMPOSIUM COMMITTEE

GENERAL COMMITTEE

ROGER N. BORCHERT *(General Chairman)* - Harris, Brown and Klemer, Inc., Bismarck, North Dakota
DONALD M. KENT *(Co-Chairman)* - University of Regina, Regina, Saskatchewan
SIDNEY ANDERSON - North Dakota Geological Survey, Grand Forks, North Dakota
ERIC CLAUSEN - Minot State University, Minot, North Dakota
DAVID FISCHER - North Dakota Geological Survey, Grand Forks, North Dakota
CLARENCE "KELLY" CARLSON - Oil and Gas Division, N.D.I.C., Bismarck, North Dakota
MALCOLM A. WILSON - Saskatchewan Energy and Mines, Regina, Saskatchewan
JAMES A. LORSONG - Serendipity Geological Consultants Ltd., Regina, Saskatchewan

REGISTRATION AND ACCOMMODATIONS

HOWARD FISHER - University of North Dakota, Grand Forks, North Dakota
LIL SINKULA - Harris, Brown and Klemer, Inc., Bismarck, North Dakota

BUSINESS MANAGER

ERIC CLAUSEN - Minot State University, Minot, North Dakota

PROGRAM

CLARENCE "KELLY" CARLSON - Oil and Gas Division, N.D.I.C., Bismarck, North Dakota
DAVID FISCHER *(Core Workshop)* - North Dakota Geological Survey, Grand Forks, North Dakota

ADVERTISING

MARY BLUEMLE - Minerals Diversified Services, Grand Forks, North Dakota
ROBERT POST JOHNSON - Harris, Brown and Klemer, Inc., Bismarck, North Dakota
ROGER N. BORCHERT - Harris, Brown and Klemer, Inc., Bismarck, North Dakota

TECHNICAL SERVICES

HOWARD FISHER - University of North Dakota, Grand Forks, North Dakota

SPECIAL EVENTS

ROBERT POST JOHNSON *(Field Trip)* - Harris, Brown and Klemer, Inc., Bismarck, North Dakota
CLARENCE "KELLY" CARLSON *(Field Trip)*- Oil and Gas Division, N.D.I.C., Bismarck, North Dakota
HUGH McCABE *(Field Trip)* - University of Manitoba, Winnipeg, Manitoba
DON KENT *(Field Trip)* - University of Regina, Regina, Saskatchewan
ROGER N. BORCHERT *(Icebreaker)*- Harris, Brown and Klemer, Inc., Bismarck, North Dakota
HOWARD FISHER *(Wine and Cheese Party)* - University of North Dakota, Grand Forks, North Dakota

EDITORIAL COMMITTEE

TECHNICAL

CLARENCE "KELLY" CARLSON - Oil and Gas Division, N.D.I.C., Bismarck, North Dakota
JAMES E. CHRISTOPHER - Saskatchewan Energy and Mines, Regina, Saskatchewan
COOPER LAND - Golden and Land Oil Company, Bismarck, North Dakota
RICHARD LeFEVER - University of North Dakota, Grand Forks, North Dakota

PRODUCTION

MALCOLM A. WILSON - Saskatchewan Energy and Mines, Regina, Saskatchewan
CHRISTOPHER F. GILBOY - Saskatchewan Energy and Mines, Regina, Saskatchewan
FRANCES M. HAIDL - Saskatchewan Energy and Mines, Regina, Saskatchewan
D. ROBERT TROYER - Saskatchewan Energy and Mines, Regina, Saskatchewan
ASSISTED BY: DOUGLAS F. PATERSON, RICHARD W. BENNETT, DAVID G. MacDOUGALL and L. KIM KREIS, *(Saskatchewan Energy and Mines, Regina, Saskatchewan)*, JAMES MacEACHERN *(University of Toronto, Toronto, Ontario)*, MICHAEL W. THOMAS *(R.W. Shirkie Geological Consultants Ltd., Regina, Saskatchewan)*, NEIL A. GROENEVELD *(Serendipity Geological Consultants Ltd., Regina, Saskatchewan)*, and HERB HAIDL *(Dr. Martin LeBoldus High School, Regina, Saskatchewan)*

NORTH DAKOTA GEOLOGICAL SOCIETY
1987 EXECUTIVE BOARD

President	Terry Roland
Vice President	Roger N. Borchert
Vice President	Sidney Anderson
Secretary	Allan Kihm
Treasurer	Alan Wanek

SASKATCHEWAN GEOLOGICAL SOCIETY
EXECUTIVE COMMITTEE, 1987

President	C.F. Gilboy
Vice President	R.W. Bennett
Secretary-Treasurer	D.R. Troyer
Business Manager	N.A. Groeneveld
Program Chairman	T.I.I. Sibbald
Past President	M.A. Wilson

FOREWORD

The high levels of exploration activities that the Williston Basin experienced from the mid-seventies through the mid-eighties produced vast amounts of new information. Many new ideas were presented at the Fourth International Williston Basin Symposium held in Regina in 1982. The recent slowdown in drilling activity has allowed geoscientists time to re-examine old data, interpret new information and formulate innovative ideas concerning a sedimentary basin of international interest. We now convene in Grand Forks to present our findings to fellow geoscientists, renew old acquaintances and exchange new ideas.

The Williston Basin has experienced several 'boom and bust' cycles since the initial oil discovery in 1951. Each boom has generated greater interest and activity than its predecessor. New fields have been studied and discussed and old fields have been re-interpreted. Even during the 'bust' periods, exciting discoveries have sparked exploration interest, as is witnessed by the recent Devonian Dawson Bay discovery in North Dakota and the Devonian Winnipegosis play in southern Saskatchewan.

The Williston Basin, North America's largest cratonic basin, contains vast exploration potential. Some plays have matured while other areas and/or deeper objectives in producing areas have been left largely unexamined. Potential exists for continuing exploration, interpretation and study.

The North Dakota and Saskatchewan Geological Societies welcome you to Grand Forks to the Fifth International Williston Basin Symposium. We are honored to host the international community of geoscientists and privileged to present approximately thirty new papers on basin geology. Earlier this week we provided a rare opportunity for geologists to examine lower Paleozoic outcrops on the northeast flank of the Williston Basin in Manitoba.

I thank all those authors who contributed to the Symposium Volume. I appreciate the time and effort of people who proofread and edited the papers, solicited advertising and did all those other things required to make this meeting a success. I am grateful to individuals and companies who contributed to the Symposium in ways too numerous to mention. Last, but not least, I thank those organizations without whose active support this Symposium could not have been held: North Dakota Geological Society, Saskatchewan Geological Society, North Dakota Geological Survey, N.D.I.C. Oil and Gas Division, University of North Dakota, Minot State University, Saskatchewan Energy and Mines and University of Regina.

Enjoy the Symposium, examine new ideas and gather new information from the technical discussions. Use this information to improve your professional skills and your understanding of the Williston Basin.

Roger N. Borchert
General Chairman
Fifth International Williston
Basin Symposium
Grand Forks, North Dakota
June 14, 1987

SASKATCHEWAN GEOLOGICAL SOCIETY CORPORATE MEMBERS, 1987

Bison Petroleum and Minerals Limited.
Regina, Saskatchewan

Canada Northwest Energy Limited
Calgary, Alberta

Canadian Hunter Exploration Ltd.
Calgary, Alberta

Central Electricity Generating Board Exploration (Canada) Ltd.
Calgary, Alberta

Chevron Resources Limited
Calgary, Alberta

Clan Resources Ltd.
Estevan, Saskatchewan

Dresser Canada Inc.
Atlas Division
Calgary, Alberta

Durama Enterprises Limited
Exploration Division
La Ronge, Saskatchewan

Eldor Resources Limited
Saskatoon, Saskatchewan

Esso Resources Canada Ltd*
Calgary Alberta

Gulf Oil Corporation
Calgary, Alberta.

Hardy BBT Limited
Saskatoon, Saskatchewan

Husky Oil Operations Ltd.
Calgary, Alberta

Jackalope Geological, Ltd.
Boulder, Colorado

Mobil Oil Canada Ltd.
Calgary, Alberta

Noranda Exploration Company Limited
Winnipeg, Manitoba

Norcen Energy Resources Limited
Calgary, Alberta

North Rim Exploration Ltd.
Cudworth, Saskatchewan

Oakwood Petroleums Ltd
Calgary, Alberta

Placer Development Limited
Vancouver, British Columbia

Potash Corporation of Saskatchewan*
Saskatoon, Saskatchewan

Saskatchewan Energy and Mines*
Regina, Saskatchewan

Saskatchewan Mining DevelopmentCorporation
Saskatoon, Saskatchewan

Saskatchewan Oil and Gas Corporation
Regina, Saskatchewan

Sceptre Resources Limited
Calgary, Alberta

Serendipity Geological Consultants Ltd.
Regina, Saskatchewan

Shell Canada Limited
Calgary, Alberta

Sproule Associates Limited
Calgary, Alberta

Suncor Inc.
Calgary, Alberta

Texaco Canada Resources Ltd.
Calgary, Alberta

Total Petroleum Canada Ltd.
Calgary, Alberta

Tri Link Resources Ltd.
Calgary, Alberta

Ultramar Oil and Gas Canada Limited
Calgary, Alberta

University of Regina*
Regina, Saskatchewan

Uranerz Exploration and Mining Limited
Saskatoon, Saskatchewan

SASKATCHEWAN GEOLOGICAL SOCIETY CORPORATE SPONSORS, 1987

Central Electricity Generating Board Exploration (Canada) Ltd.
Calgary, Alberta

Elmore Oils Ltd
Calgary, Alberta

J.D. Mollard and Associates Limited
Regina, Saskatchewan

Nautilus Exploration and Associates
Regina, Saskatchewan

Placer Development Limited
Vancouver, British Columbia

R.W. Shirkie Geological Consultants Ltd.*
Regina, Saskatchewan

Unocal Canada Limited
Calgary, Alberta

SASKATCHEWAN GEOLOGICAL SOCIETY CORPORATE DONORS, 1987

Jackalope Geological, Ltd.
Boulder, Colorado

Placer Development Limited
Vancouver, British Columbia

Regal Petroleum Consultants
Estevan, Saskatchewan

Taiga Consultants Ltd.
Calgary, Alberta

United Tri-Star Resources Ltd.
Calgary, Alberta

Corporate support is an important source of Saskatchewan Geological Society funds, and enables the Society to maintain vigorously its wide variety of geoscientific activities. Such support is also valuable in that it confirms to individual members that our goals are shared by industry. The Society therefore acknowledges with deep gratitude the contributions it has received from the organizations listed above (Corporate Membership, $100.00; Corporate Sponsorship, $50.00; Corporate Donorship, $25.00), and encourages others to join their ranks.

*Awarded by the S.G.S. Executive in acknowledgement of services rendered that greatly exceed in value the fee for the appropriate category of corporate support.

NEW OIL FROM OLD IDEAS: AN HISTORICAL REVIEW OF WILDCATTING IN "FRONTIER SASKATCHEWAN"

S.P. (STEVE) HALABURA

North Rim Exploration Ltd.
Box 388
Cudworth, Saskatchewan
S0K 1B0

INTRODUCTION

During the summer of 1986, the author, with the support of the Saskatchewan Geological Society, embarked on a project to compile an oral history of the early days of the Saskatchewan oilpatch. The process of collecting the story is by no means complete as of yet, and this paper is meant to be a preliminary summary of the data gathered to date. It is based on conversations and written notes with numerous explorers of the time. The purpose of this paper is three-fold. Firstly, it will provide a general background summary of the events leading to the first true oil boom in the Province which occurred from 1948 to 1958. Secondly, it will look at some of these early explorers' concepts and the problems they encountered in their role as exploration geologists in "Frontier Saskatchewan." Lastly, this paper might suggest alternatives to ideas which have been drawn from their early efforts and are currently held by explorationists with respect to the barren central portion of Saskatchewan.

During this period, the frontier explorers discovered two major sources of light and medium oils in the Province, namely the Lower Cretaceous/Jurassic reservoirs of the Swift Current Platform in southwestern Saskatchewan and the Mississippian subcrop reservoirs in southeastern Saskatchewan. Subsequent to these discoveries, Jurassic shoreline sands and Mississippian subcrops have dominated the thinking of explorationists and provide the bulk of Saskatchewan oil plays (apart from heavy oil reserves). Other plays, such as the light gravity Viking oil play and the heavy oils of the Lloydminster area in west-central Saskatchewan, predate this first boom.

The Jurassic and Mississippian play concepts met with failure beyond the Swift Current Platform and the subcrop of the upper part of the Lodgepole Formation. As late as 1969, when Pheasant Exploration Ltd. drilled 49 dry holes while probing Winnipegosis reefs in central Saskatchewan, the remainder of the Province had not seen a successful oil pool discovery.

Does this mean that central Saskatchewan is barren? In large parts of the Province, the only subsurface data presently available consist of either early wildcat wells or potash exploration tests which are not specifically targeted to find oil and gas. Considering that our data base in this region is derived from these early explorers' efforts, would it not be a worthwhile exercise to understand the tools, methods, and play concepts used by these explorers when they selected their rank wildcat targets? I hope in this paper to discuss some of these aspects.

The oft-quoted geologists' proverb uttered by Wallace Pratt, namely that oil is found in the minds of men, has interesting implications. If the data we use day to day are the result of these original exploration ideas, would it not help our understanding of a particular region's oil and gas potential if we knew what these ideas were? Much work, research and discussion remain; however, let us begin our quest.

ANATOMY OF A BOOM

PRE-BOOM EXPLORATION EFFORTS

Contrary to the luck of the early wildcatters of Texas, Oklahoma, the Illinois Basin, and other oil patches of the U.S.A., the early wildcatters of Saskatchewan were not that successful. The first well drilled in the Province was at Belle Plaine in 1888[1], reaching final depth in the "Lower Pierre" at 1551'. From 1888 on, other wells were drilled, but they were largely syndicated drilling efforts, punched down by cable tools and often beset by financial and drilling problems (for example, Moose Jaw No. 1 well, located in Section 32, Twp. 16, Rge. 26 W2M, which was spudded in 1913, and finally abandoned in 1932). The Coutts Syndicate, along with Coalgate Oils and Franco Oil and Gas Ltd., met with some success at Kamsack in 1937 when non-associated gas was found in the shallow Favel shales. Unfortunately, the Kamsack gas wells provided only enough methane to fuel a farmhouse, and if it was of particularly good deliverability, the farmer's barn as well.

One of the earliest explorers to mount a systematic exploration program in the Province was Imperial Oil Ltd. Imperial was not to be outdone by mere promoters, for wells were drilled at the Boundary No. 1 (4-8-1-27 W3, 1916), Fusilier No. 1 (Sec. 23-34-28 W3M, date unknown but pre-1940), and Muddy Lake No. 1 (11-7-39-22 W3, 1919) locations. These were shallow tests and all were dry. Imperial is to figure most importantly in the following portion of the chronicle.

IMPERIAL OIL AND THE NORTHWEST COMPANY

Imperial Oil Ltd. had vested interests in finding oil in Western Canada, especially Saskatchewan. On September 19, 1916, Imperial completed a refinery in Regina in order to supply regional western markets with fuel products. It initially processed 1500 barrels of crude per day, the supply coming from Wyoming. The presence of a refinery plus a local demand led to Imperial's initial exploration efforts in the Province.[2]

Imperial had first become active in the Province in the early 1900s through its Winnipeg-based subsidiary, the Northwest Company. Geologists, beginning in the Manitoba outcrop belt, had systematically worked their way across Canada's western provinces to Norman Wells in the Northwest Territories. The field mapping parties defined prospects which were

1. All references to pre- and post-1949 wells were obtained from the Government of Saskatchewan Department of Mineral Resources "Schedule of Wells Drilled for Oil and Gas to December 31, 1952," published in 1953.

2. Anonymous, "Oil in Saskatchewan," 1966, p. 40.

drilled by numerous tests, leading to the discovery of oil at Norman Wells in 1920[3]. Apart from this success, all the other wells were dry and abandoned.

Throughout the following years other refineries were opened, including the Hi-way Refineries Ltd. plant, located in Saskatoon in 1932, the British American refinery situated in Moose Jaw in 1934, and others. In 1935, the Consumers Co-op refinery opened in Regina, further adding to the processing capability of the Province.[4] During these pre-war years, Imperial's efforts had followed the Rockefeller philosophy of establishing control of pipelines, crude oil transportation, and refining capabilities. Spurred on by World War II, Imperial was to mount the most concerted effort to date to find local oil and gas reserves.

World War II had a profound effect upon industry and commerce in North America, and the oil business was no exception. Upon entering the fray in Europe, the Canadian Government realized that secure oil supplies were essential for the war effort, and began to encourage oil companies to explore. Of all the early explorers, Imperial was by far the most technically advanced in terms of subsurface understanding of potential oil reserves. In 1939, huge exploration reservations were offered to the Northwest Company, a subsidiary of Imperial Oil. These Northwest Company permits, coupled with Imperial acreage picked up in 1940, 1941, and 1942, covered most of the Province.[5] It must be remembered that during this period, there was no formal method of acquiring exploration leases or permits from the Government of Saskatchewan. In 1942, the Northwest Company changed its name to Norcanols Oil and Gas and continued its search in conjunction with its parent, Imperial.

Fig. 1 A Norcanols/ Imperial rig in Saskatchewan in 1944 (locality unknown). COURTESY OF IMPERIAL OIL ARCHIVES.

Imperial had assembled an expert team in Saskatchewan with Dr. J.C. (Cam) Sproule in charge of exploration. A head office was established in Moose Jaw with field parties, including seismic and core drilling crews, sent out across the Province from this base. Charlie Visser and Vern Hunter were in charge of the actual drilling. During the period from 1939 to 1946, the Imperial and Norcanols team drilled 15 wells, 8 as Imperial and 7 as Norcanols.

On May 8, 1942, the team was prepared to drill its first well.[6] The Norcanols (Northwest Company) Radville No. 1 well was spudded in Lsd. 16, Sec. 36, Twp. 5, Rge. 19, W2M near the town of Radville, Saskatchewan. A National Ideal Type 100 Heavy Duty Rotary Drilling Rig, under the direction of driller R.A. Burns and geologist Gordon Beard, was assigned the task. The Government of Saskatchewan, as one of the conditions of issuing the drilling license, required that all horizons carrying water, gas, and oil be noted, along with weekly drilling reports upon official forms, which Dr. Sproule found "complicated."

The first geological marker, the Glauconite "A" Zone, was penetrated at 390'. Surface casing was set within the Lea Park (Bearpaw Group) at a depth of 602.' Below this, the drilling proceeded at a monotonous rate, with the only markers of interest being various microfossil zones meticulously identified by the Imperial team, such as the "Ammobaculites Milliammina" Zone. At 3470' the bit penetrated the "Morrison" Formation (probably the Blairmore). The first Jurassic formation to be penetrated was the "Sundance" Formation. A bit of excitement was generated when a gas show was noted in the "Morrison"; however, no drillstem test was taken. The bit dug on, passing through the Seismic "C" Reflection horizon, noted to be a "Limestone Marker, in part oolitic," from 4315' to 4380.'

Then, true excitement: a carbonate sequence was penetrated, and R.T. Wickenden noted "Endothyra" in cores, identifying the rocks as being of the "Carboniferous." In the dark grey limestones of the "Charles Formation," oil was noticed. A drillstem test taken from 5070' to 5103' recovered 375' of drilling mud with some gas bubbles and oil globules. The second test run from 5070' to 5164' recovered 1700' of black sulphur water and drilling fluid. In both tests it should be noted that the actual packer settings were over a greater interval than the oil zone, thus increasing the interval of the test. This was a common Imperial practice of testing very wide intervals as opposed to trying to isolate the particular zone of interest.

Upon resuming drilling, the normal procedures of cutting cores in porous zones and meticulously logging the samples continued. The "Kinderhook," or Bakken Formation, was noted at 6190'. In the deeper Paleozoics, from the Birdbear

3. For an excellent account of Imperial Oil's efforts in Western Canada, please refer to "Oil in Canada West" by George de Mille, printed by Northwest Printing and Lithographing Ltd., Calgary, Alberta in 1970.

4. Anonymous, "Oil in Saskatchewan," 1966, p. 40-41.

5. Jack Porter in interview, March 4, 1987.

6. All technical data concerning the Imperial/ Norcanols wartime wells have been obtained from individual well files available for examination at the Geodata Section, Saskatchewan Energy and Mines, Regina, Saskatchewan.

Formation to the Dawson Bay Formation, the sample descriptions read:

> *Buff and brown limestones and dolomites, many of them porous, vuggy, and oil stained; anhydritic; some brick red argillaceous dolomite and green shales in upper part.*

Then, another curious subsurface formation was penetrated. From 7590' to 7842', a thick salt zone was drilled. Though this salt was noted in an earlier well core from western Saskatchewan, it was not to achieve significance until revealed in this well. Ed Swain, an official with the Department of Mines, wrote in a memo to the Deputy Minister dated August 24, 1942:

> *On Saturday, August the 22nd, about 11:00 a.m., I was informed by telephone that happenings of note were occurring in the Radville well and that unless visited immediately there was a possibility that the event might be missed entirely. This information was given to me by Mr. Fairley, the inference made was that the bit had or was about to encounter oil production.*
>
> *Knowing that the horizon was either in Lower Devonian or Silurian formation which gives production in other parts on this continent, I lost no time in visiting the well. At 2:30 p.m. I inspected the mud pit and saw no signs of oil whatsoever, there was not even any odour which one could detect and I found that the bit was then at 7837' from the surface, the last 235' had encountered a solid body of rock salt.*

Swain was convinced that the well was penetrating the Salina Beds, a salt sequence present in the Michigan Basin. This correlation led to the belief that the Prairie Evaporites, including the Winnipegosis Formation, were Silurian in age. This confusion was to last into the mid-1950s. Swain also emphasized the possibility of solution mining the salt, for wartime demand for salt was high. Later, Dr. Thorvaldson of the University of Saskatchewan analyzed a pinkish mineral found in the core and found it to be potassium chloride or potash. After this point, the well was taken to a total depth of 7958'.

At this point, the records of the D.M.R. become confusing in terms of operations. Mechanical difficulties are noted on the striplog, for apparently the drill string twisted off at 7958' with the top of the fish at 4212'. Fishing continued until early September, 1942. On September 19, 1942, a whipstock was cemented at 4912' and the hole was diverted to a depth of 6062,' with a 7" casing set at 5164'. Then a second fish was lost at the bottom of the deviated hole and was not recovered. The frustration of lost tools in the hole is a daunting challenge today; one can imagine the problems they would have caused in 1942.

It was decided to test the various oil and gas zones in the "Charles" and "Morrison" through perforations in the 7" casing. The first perforations were placed from 5103' to 5116'. Again, Imperial was beset by problems, for the perforations were placed directly below the zone of interest which extended from 5091' to 5104'. The zone was acidized with 300 gallons of 15% acid, whereupon the well produced sulphurous black water with oily foam at a rate of 10 barrels per hour. It was only after the test was completed that it was discovered that Halliburton had made an error in measurement and had in fact perforated too low. The perforations were cemented off; however, the equipment broke down before the cement job was completed. The second set of perforations were placed from 5080' to 5091', this time directly above the zone of interest. Again, after acidizing, the well flowed 10 barrels of sulphurous salt water along with some free oil. It was noted that the oil was 10° API, and a note was made that the test was inconclusive due to the faulty cementing of the previous perforations. The third set of perforations were higher in the Charles, from 4950' to 4980', again placed over a large interval. Only salt water was recovered. Two zones were perforated in the "Morrison," but only salt water was recovered.

After a grueling period coupled with fishing jobs, whipstocks, and mechanical difficulties in perforating the pay zone, Imperial had perhaps made a commercial oil find in southeast Saskatchewan. Unfortunately, the evidence was inconclusive, for the oil was heavy and made no effort to flow to the surface under its own pressure. The well was finally abandoned on January 8, 1943, with 7" and 13 3/8" casing shot off and removed. The cost to October 30, 1942 for the well was $208,380.00, quite a sum for 1942.

Driller Burns, geologist Beard, and the National Type 100 rig now moved off the Ogema. The new well spudded on February 28, 1943 at Lsd. 4, Sec. 24, Twp. 7, Rge. 23, W2M. If Dr. Sproule and his cohorts believed that the difficulties encountered at Radville No. 1 were an isolated occurrence, they were sorely mistaken, for the dreaded "Silurian" salt was to create difficulties again.

The uphole drilling was fairly routine, encountering the Bentonite "A" seismic and Limestone Marker "C" seismic reflection horizons as was expected. Again, gas was encountered in the "Morrison" (probably Blairmore) at 3466'. Though no well-developed sands were observed, a drillstem test was run over the interval 3416' to 3561', with the tool opened for a 4' interval directly below the top packer. Salt water, which bubbled vigorously with a blue odourless gas, was recovered in the test. The gas was of sufficient quantity for samples to be obtained, and it tested 83% methane and 15% nitrogen, with the remainder being CO_2, and ethane by analysis at the Department of Mines and Resources in Ottawa. The closed-in pressure reached 1100 lbs. Despite this recovery, Dr. Sproule was unimpressed, for he indicated that if the show was commercial it would have made its presence known in a more dramatic fashion. This conclusion was reached despite the fact that a core cut in the interval had only 26% recovery, possibly indicating a poorly consolidated sand which may have washed out. The precise sand interval was also not determined. The show would be evaluated again later through casing.

The Charles Formation was soon reached, with the Endothyra Zone noted from 4970' to 5003'. Porosity was present, along with a thin porous dolomite in the Lower Charles which had petroliferous partings. The zone 4777' to 4823' was tested, but only recovered 44' of drilling fluid. Another oil show was encountered in the Devonian limestone sequence from 6615' to 6659', in a "light brown, porous, and petroliferous limestone in the Devonian Group". This zone was not tested. There were two other minor oil shows in samples from 5795' to 5800' and again from 5880' to 5920', but these were not considered worth testing due to the apparent lack of porosity in samples.

Drilling continued until the top of the "Silurian" salt was reached at 7317' on or about June 15, 1943. The bit made progress to a depth of 7688', where it became "frozen" upon entering the Winnipegosis Formation. Once again, the salt was to play havoc with the drilling. On June 21, 1943, fishing attempts were begun. By July 10, 1943, the top of the fish was still at 5464' with the pipe cutters milling at 5776'.

On July 28, still no progress had been made, so it was decided to cement the fish in place and whipstock the hole. Further difficulties were encountered in running the whipstock, with the final whipstock planted at 5347'. The whipstock was then drilled past on or about August 11th. The fishing attempts were complicated by numerous bridges and caving in

Fig. 2 Moving the drawworks through Truax, Saskatchewan (near Wilcox, Parry, Dahinda, and Ogema wells).
COURTESY OF IMPERIAL OIL ARCHIVES.

the hole requiring cleanout trips and much reaming. Prior to these misadventures, Swain had felt concern for Imperial and consulted with Professor Worcester concerning an ideal drilling mud for Saskatchewan. He was thanked for this concern by Dr. Sproule in a letter dated June 8, only days before the onset of the problems.

In order to prevent a similar problem in the deviated hole, casing was run and set at 7634'. From this point, the records indicate no further difficulties. Due to these numerous problems, discontinuous Halliburton logs had to be run. Total depth in the Precambrian was reached some time during the last week of January 1944. Porous sands were noticed in the Winnipeg, so two drillstem tests were run to test the sands for any sign of hydrocarbons. Again, the tests were over wide intervals - 204' in test 3 and 120' in test 4. No hydrocarbons were recovered in either of the tests.

Imperial was now ready to begin testing the uphole petroliferous zones which were behind casing. Unfortunately, these tests were also to be expensive failures due to faulty equipment and crew errors. The first zone to be tested was the oil stained porosity in the "Devonian" from 6615' to 6650'. In the first run, out of 40 intended shots, only 3 actually fired. Further mechanical problems with the guns caused an extra 14.5 hours of time, a fact noted by the cost-conscious Dr. Sproule to his superior, Mr. O.C. Wheeler in Toronto.

When the perforations were allowed to flow the next morning, only a large mud recovery was obtained, leading Imperial to conclude that there was no cement shutoff above the perforations. A cement squeeze through the perforations was then attempted and was apparently successful. However, due to problems with a packer, the test was left unfinished. It must be remembered that all of this was done in the middle of January in the unprotected plains of Ogema, not exactly noted for its tropical winter climate. Finally, on January 3, 1944, a hookwall packer was set but the test recovered only salty sulphurous water with no oil.

The "Kinderhook" (Bakken) was next tested but recovered only 5280' of black sulphur water. Two more tests, one of the Charles and the second of the Morrison, recovered only salt water and "sulphate" water. After this last test on February 12, the well was ordered abandoned.

It must be remembered that this well was plagued by several problems, namely:

- severe drilling and mud problems due to abundant anhydrite and salt;
- severe mechanical difficulties in perforating and cementing; and
- difficulty in obtaining the potential hydrocarbon-bearing zones due to discontinuous logging intervals, poor logs, and the masking of shows by poor muds and long test intervals.

Considering the problems that these early explorers faced, it is not surprising that oil was not discovered. These two initial wells impressed upon Imperial the nature of the beast that it was up against.

While Norcanols was undergoing its tribulations at Ogema, Imperial drilled a well on one of its own permits.

Imperial Dahinda 10-23-10-23 W2M was spudded on March 13, 1943. This well was drilled rather uneventfully due to the fact that the well did not penetrate the "Silurian" salt but

reached total depth only in the Upper Devonian. Again, no oil was recovered on drillstem tests and the well was abandoned on July 10, 1943.

Norcanols Parry No. 1, located at 16-8-9-21 W2M, was spudded on July 8, 1943, and also found the "Silurian" salt absent. Though Dr. Sproule could correlate the "Kinderhook" and the Devonian "grey" beds, the salt beds of the "Silurian" were missing. Again, the Elk Point sequence was correlated to the Silurian and not the Middle Devonian. The absence of salt in this well would lead Doug Layer, chief geologist for Imperial, to comment in later years that the salt found in the lower section of the Paleozoic was deposited in isolated pans as opposed to a widespread continuous layer. This belief would later have an impact on Bob Bishop of Sohio Petroleum and his theory on salt solution.

Dr. Sproule was also surprised at the amount of dolomite, particularly the "magnesian" variety, and the lack of limestone in this well. Anhydrite was also present in large quantities. The fact that anhydrite could be seen in significant amounts in samples suggests that Imperial was beginning to understand the role of designing muds specifically for the Williston Basin and was having some success in improving them. Four zones of "porous and petroliferous" limestone and dolomite were recorded; however, only salt water and sulphurous salt water were recovered upon testing. The "Morrison" gas horizon also present at Ogema and Parry, tested "sulphate" water. As with the Ogema well, the through-casing production tests were plagued with perforation guns that did not fire, unsuccessful cement jobs, the lack of informative logs, and the presence of fluid communication between zones behind the pipe. The well was abandoned on February 10, 1944. It had been drilled in what was for Imperial a record time, no doubt due to a better understanding of proper muds for the Paleozoic section, the immediate running of casing through troublesome zones, and the testing through pipe of prospective zones as opposed to openhole DSTs.

The veteran of Radville No. 1 and Ogema No.1, the National Type 100, was set up at Norcanols Imperial Wilcox No. 1 at the boundary between Lsd's 15 and 16, Sec. 32, Twp. 13, Rge. 20 W2M on Norcanols Reservation No. 136 on March 19, 1944. In this well, the Imperial team was surprised to find the presence of a sand and shale sequence in the Sundance immediately underlying the Morrison gas sand. These "Sundance" sands were not present in any previous wells. A 100 foot interval was tested but only warm salt water was recovered, dampening the excitement of Imperial and a Mines Branch agent (the indomitable Mr. Swain, who seemed to love wellsites at 3:00 a.m.). The crews were ever vigilant for porosity in the limestone section, as Dr. Sproule had warned his geologists that the location of these porous zones was still uncertain. Only gross lithological similarities could be correlated, such as the "Kinderhook" (the Bakken), the Devonian red shale (the Three Forks), and the "Salt'.' In previous memos to Mr. Swain, Dr. Sproule had insisted on the importance of numerous water analyses of subsurface fluids, for such tests would help Imperial determine whether the fluids produced on DSTs were from the formation or if they were "put there by us'.' Another test was run over the "Endothyra" Zone of the Charles, and upon opening the tool, salty and sulphurous water flowed over the top of the drill pipe. The well was abandoned on June 16, 1944.

The National then moved to Norcanols Gap. No. 1 at 16-3-3-25 W2M on July 23, 1944. Total depth was 7767' and was reached and completed November 3, 1944. The well bottomed in the Devonian and did not attempt to penetrate the Lower Paleozoic section. It appears Imperial was learning that the zones most likely to produce oil included the Morrison, the Charles, the "Kinderhook," and the upper limestones and dolomites of the Devonian.

Gap No. 1 encountered uphole problems due to cavings, and only three drillstem tests were run over the Morrison sand, believed by Imperial to be gas-prone in the region. Only one of the tests proved to be successful, as the other two ran into mechanical problems including poor packer seats and cavings jamming the testing tools. The only successful test recovered 30' of mud.

The surprise found in this well was a 1490' thick Triassic "Spearfish" formation composed of red and green argillaceous dolomites, sandy dolomitic shales and siltstones present from 5290' to 6780'. The Madison Formation, from 6780' to 6978' was not the typical "Charles" but rather dark argillaceous limestones and cherts. This caused great consternation among the Imperial group. Why was the Mississippian so thin and the red beds so thick? It would require further drilling to find an answer to this problem.

One of the precepts of the oil business is that oil is where you find it. Having found some oil at Radville No. 1, Norcanols Radville No. 2 was drilled at 16-36-5-19 W2M, 900' from the previous Radville No. 1 location. This well was intended to be a Charles test in order to evaluate properly the oil show. After all, Imperial had learned so much about muds, drilling techniques, and methods of evaluation over the past two years that perhaps this time oil would be found in commercial quantities. The petroliferous horizon was present in the Charles "Endothyra" Zone as at Radville No. 1, and upon hearing this news, Mr. Swain, ever mindful of the Province's interest, rushed out to the scene. The show must have been very impressive, for in a memo to his boss, Mr. Swain writes:

> *I was present at the well continuously until 10 at night, as this is a matter of deep concern to the welfare of the Province in the case the (drillstem) test showed a commercial oil horizon.*

Unfortunately, Mr. Swain was to be disappointed for the drillstem test recovered only drilling mud, with no evidence of oil in commercial quantities. A second test was run over a lower horizon and only 2 gallons of dark brown oil were recovered along with sulphurous salt water. The well was abandoned and moved to a location at 11-20-13-13 W3M on an Imperial reservation in southwest Saskatchewan.

Imperial Swift Current No. 1 was a deep test, spudded on October 5, 1944 and completed on April 1, 1945. It was drilled down to basement and as usual intermediate casing was run. An interesting zone in the "Lea Park" (the Milk River) was discovered to have a gas show which was later tested through perforations. The well produced 11.9 Mcf/d but was abandoned because the production was not considered to be of sufficient quantity to be economical. No shows were noted in the deeper horizons.

At this point, a pivotal event occurred in Saskatchewan. In August of 1944, the Cooperative Commonwealth Federation (C.C.F.) under the leadership of Tommy Douglas was elected as the new government of Saskatchewan. The election of a "socialist" government by the people of Saskatchewan did not sit well with the Imperial management in Toronto and New York. Common legend has Imperial "moving out their seismic crews for Alberta on the night of the election," and "trucks being loaded with anything of value minutes after the election,

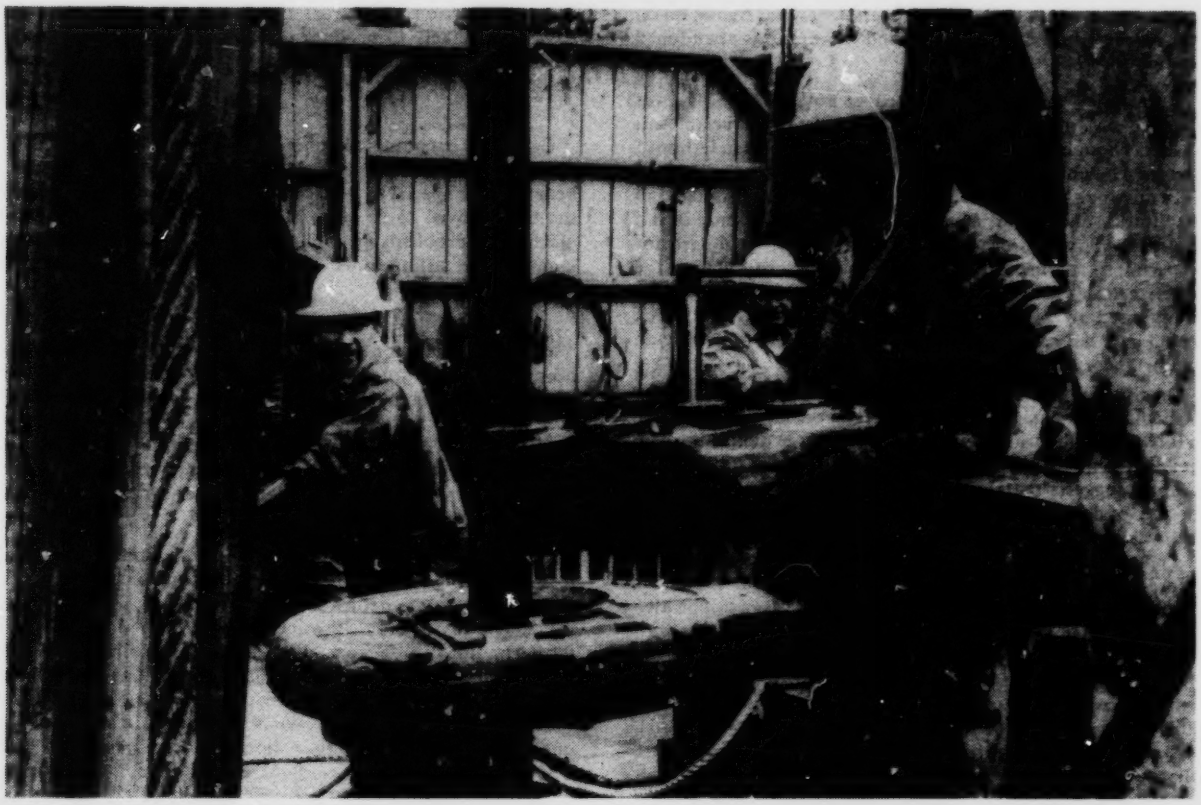


Fig. 3 Imperial drilling crew in action in Saskatchewan, 1944.
COURTESY OF IMPERIAL OIL ARCHIVES.

all pointed to Alberta." Yet the facts do not support this myth. Imperial, including Norcanols, continued to drill wells on their permits in Saskatchewan, the remaining wells being:

Imperial Elbow No. 1, 12-25-23-6 W3M, spudded December 17, 1944;
Norcanol Imperial Pennant No. 1, 4-14-18-16 W3M, spudded April 22, 1945;
Imperial Morse No. 1, 1-16-18-7 W3M, spudded July 10, 1945;
Imperial White Fox No. 1, 5-14-52-14 W2M, spudded August 11, 1945;
Imperial Davidson No. 1, 16-8-27-1 W3M, spudded November 1, 1945; and
Imperial Davidson No. 2, 13-10-29-2 W3M, spudded February 21, 1946.

According to C.A.L. (Vern) Hogg, the Deputy Minister of Natural Resources during this period, what actually led to Imperial's decision to leave Saskatchewan was a simple matter of the expiration of the original permits issued to Norcanols and Imperial from 1940 to 1942. According to Vern Hogg, Imperial's manager for Canadian operations (no doubt Mr. O.C. Wheeler) came out to talk to government officials during the fall of 1945 from head office in Toronto. The government under Tommy Douglas was willing to extend to Imperial essentially the same reservations, under the same terms, as had been granted during the war years. The government wanted to see economical oil and gas production established, as this would add to the wealth of the Province. Certain "cosmetic" changes were made by the government, none of which would have materially affected the economic spirit of the deal; however, Imperial walked out on the deal extension, refusing to agree to the terms of the extensions. Perhaps Imperial allowed the permits to expire, not because of the "socialist" government, but because of its problems and lack of any discoveries of commercial quantities of oil and gas. Drilling which was done subsequent to the C.C.F. victory was simply to evalute the remaining prospects.

The Norcanols and Imperial Crown permits, drafted under a Liberal government during a time of national crisis, were allowed to expire; however, conversations with certain key figures indicated that Imperial had enough encouragement during this early drilling to keep its hand active within the Province. Some anti-C.C.F. feelings were no doubt present for Imperial now adopted the strategy of purchasing freehold leases in southeast and south-central Saskatchewan, thereby avoiding the need to deal with an anti-business (or so they perceived) regime. Governments were not to be trusted, so better to own privately-owned lands as opposed to lands subject to the whims of the Crown.

April 1946 marked the end of Imperial's efforts in Saskatchewan. Imperial's lack of enthusiasm is noted in the Saskatchewan Energy and Mines well files, where little technical information is present. The plays also seem suspect. For example, in the case of White Fox No. 1, the justification for taking over the ongoing operations of Bobjo Mines was a reported gas seep on the banks of the White Fox River.

COMING UP TO A GREAT LAND RUSH

After the Imperial Norcanols exploration program, but before the Great Land Rush of 1948, there was some exploration activity in the Province. The primary discoveries in the Province during this period occurred in the Lloydminster area, where numerous small companies discovered heavy oils in the Lower Cretaceous sands. Most of these companies were operating from leases, not the large exploration reservations which were to follow. Numerous pools were discovered; however, the oil was heavy, and it was very difficult to market with the purchasers buying this oil for paving and the production of lower grades of fuel oil. Heavy oil shows had been noted in the Colony Oil and Gas Co. Ltd. Colony No. 3, 5-19-49-27 W3M, spudded on October 24, 1936 within the Lower Cretaceous "Blairmore" Formation, but it was not until National Grant No. 1, spudded on November 7, 1944, at 4-14-49-28 W3M, that a commercial oil well was completed. Heavy black oil was produced from the Sparky Sand of the Lower Mannville.

Among the heavy oil pools discovered at this time were Silverdale (April 1945), West Lashburn (May 1946), Lone Rock (February 1947), Landrose (July 1948), Dulwich (November 1948) and Gully Lake (October 1949). These discoveries were largely due to previously developed oil pools on the Alberta side of the Lloydminster heavy oil belt. The vast undrilled portions of the Province were intimidating to many of these small explorers as no oil had been found in commercial quantities. All this was about to change in 1948, largely due to two factors: Leduc, and the C.C.F.'s exploration reservation system.

THE SASKATCHEWAN OILPATCH BREAKS OPEN

Beginning in 1948, the period which follows marks one of the greatest periods of exploratory activity that the Province has ever undergone. Perhaps the best way to chronicle the numerous developments which occurred during this time is to follow the exploits of one of the wildcatting companies, namely the Sohio Petroleum Company of Cleveland, Ohio. Others, such as the Tidewater Associated Oil Company Operator, Phillips, British American, and Albercan were also active; however, it is beyond the scope of this paper to chronicle all activity. I will save this story for later telling.

In June of 1949, Robert A. Bishop, a recently independent consulting geologist, was at the Alberta Society of Petroleum Geologists Annual Golf Tournament. There he met Carl Nickle, publisher of the Nickle Oil Bulletin, who decided to give Bishop some advice:

> *Go to Regina and apply for permits, any Crown Permits available. They are going fast. It will cost you $250.00 per permit filing fee and you can sell them easily.*

Bishop was intrigued by this advice, but did not act upon it as he knew little about Saskatchewan and the Williston Basin. Besides, Joe Irwin, a prominent Calgary consultant, had advised Bob not to go out to Regina. Irwin told Bob that as a consultant, Bob had no business competing with the people he was advising[7].

Bob was not be be rid of Saskatchewan that easily. Bob had sold some maps of the Peace River area to Sohio Petroleum Ltd. under the command of Mr. Harry Ross, Sohio's exploration manager in Canada. Ross liked Bob's maps so much that he offered to hire Bob as an employee. With his fledgling independent wings just unfurled, Bob was hesitant about becoming a company man. In an effort to dissuade Ross, Bob asked for the sum of $12,000.00 per year, an exorbitant wage

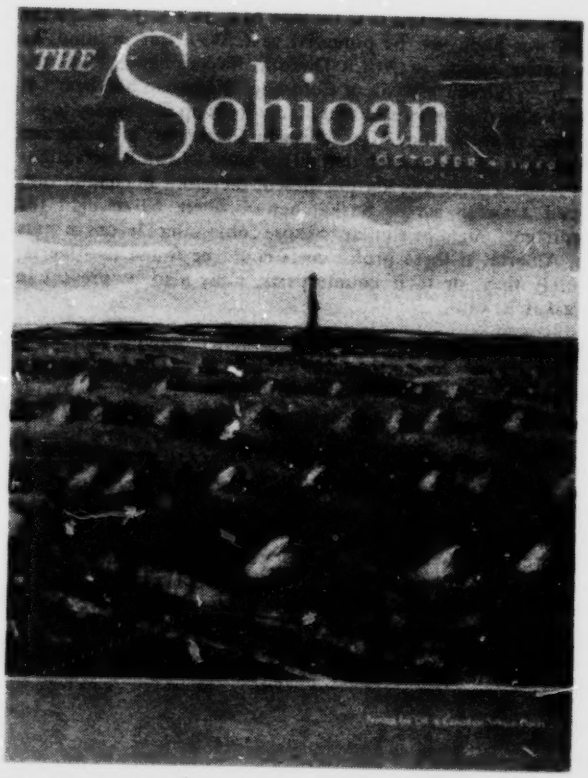


Fig. 4 Sohio displayed its interest in Saskatchewan on the cover of the October 1950 issue of the "Sohioan," the company newsletter.
COURTESY OF BOB BISHOP.

in those days. Much to his dismay, Ross accepted, and Bob soon found himself in Regina running Sohio's exploration efforts in the Province.

Standard Oil of Ohio Co. (Sohio for short) was the original Standard company founded by John D. Rockefeller back in the mid-1800's. Sohio was primarily a refiner, marketer, and shipper of petroleum products, leaving the risky business of exploration for others. In the late 1940s, Sohio saw the need to find and develop its own secure sources of crude oil so George Buchanan, Vice-President of Exploration for Sohio, was given the task to meet this mandate.

Fig. 5 Sohio exploration meeting, 1949.
FROM THE OCTOBER 1950 "SOHIOAN," COURTESY OF BOB BISHOP.

7. Bob Bishop in interview, February 8, 1987.

Buchanan believed that the company had to go where the risk was high, yet the potential vast. With this in mind, he initiated leasing in North Dakota, Saskatchewan, and the Denver-Julesburg Basin of Colorado. Buchanan had heard of the Leduc discovery and sent Harry Ross up to Calgary to get a piece of the action. After following the activity at Leduc and Redwater, Buchanan felt that all the good Crown Reservations in Alberta were already purchased; therefore Buchanan outlined a swath across Saskatchewan where he thought the sediments might be similar to those containing Devonian reefs in Alberta. If these profile reefs could be found in Alberta, surely they, or their counterparts, must also be present in Saskatchewan[8].

This initial foray by Sohio into Saskatchewan illustrates two major reasons for getting into the Province. The first was the availability of large exploration reservations owned by the Crown and made available to explorers at low cost.[9] The regulations had been brought into place in 1945, and originally allowed subsurface permits of up to 34,650 acres and geophysical permits of up to 250,000 acres. The term of these permits was 21 months with work requirements attached and strictly enforced.[10] Under C.C.F doctrine, the leasing of Crown Lands to the private sector en masse was not appealing, so in 1949, under the direction of C.A.L. Hogg, Deputy Minister, the "Crown Reserve" was established, whereby the Crown had the right to reserve 25% of the permits as undisposed Crown Reserves.[11] The chief architect of government oil and gas regulations was C.A.L. Hogg who was responsible to the late Honourable John M. Brockelbank, Minister of Mines and Natural Resources.

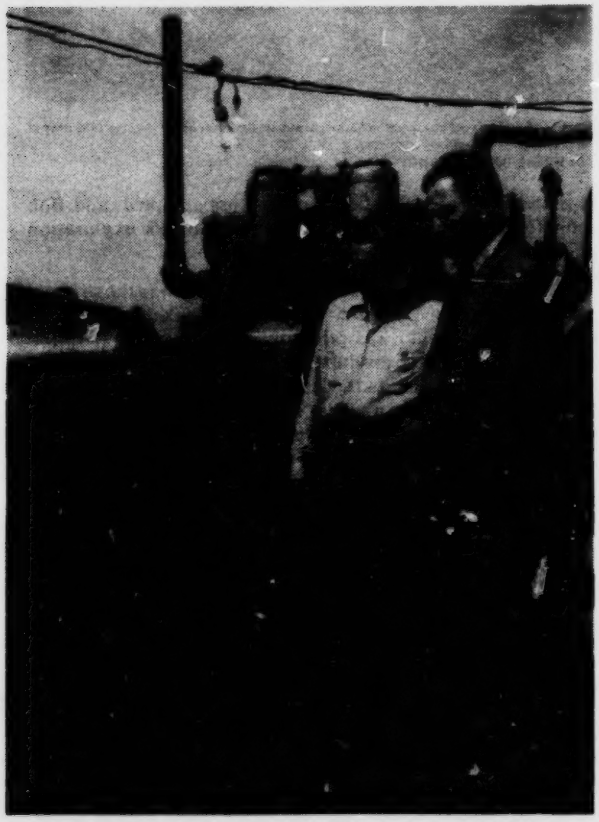


Fig. 6 Vern Hogg (left) and the late Honourable J.H. Brockelbank at rig site in 1950. COURTESY OF C.A.L. (VERN) HOGG.

Under these regulations, anyone could file for a permit, pay a nominal fee, and be given the right to explore for oil on the permit lands. Of course, the key word here is *explore* as work commitments were an integral part of the system.

Some of the big players were again becoming active in the Province. Imperial had changed its philosophy and was acquiring freehold lands in southern Saskatchewan as did Shell and certain others. The first freehold brokers, better known as leasehounds, began trickling into southeast Saskatchewan in 1947.

The second impetus to the great land rush was Leduc, discovered in 1947. Leduc proved that commercial quantities of light crude oil could be found on the Prairies. Leduc also provided an exploration concept, that of the Devonian reefs. Speculators and bonafide explorers could see the potential for deep reefs in the subsurface of Saskatchewan simply by applying the process of trendology. The students of the Norcanols/ Imperial wells might have had difficulty in accepting this, as the section contained the Silurian salt and a basal dolomite which may or may not have been the "Winnipegosan" dolomite of the Manitoba outcrop. Nevertheless, those who rushed to Leduc and Redwater in 1947 and 1948 largely duplicated the experience of Sohio, and found themselves to be "Johnnie-come-latelies" in the Leduc play and therefore had problems finding choice permits. Yet in the next Province over . . .

Overnight, or so it seemed, the speculators and explorers swarmed across Saskatchewan, picking up any piece of freehold they could find and file on any permit they could post. It did not matter where or why you got your permits, as long as you got your chunk of the potential wealth. In most cases, little thought was given to applying geological knowledge to permit selection because little was known of the sedimentary sequence. One must remember that these explorers were plagued with the same problem that haunted the earlier explorers: the majority of the Province is covered by glacial drift, making the surface mapping of subsurface structures impossible.

There was, however, a problem with the permits in that they had a life span of only 21 months. If a speculator had purchased a permit in June of 1948, the permit would have to be validated by drilling or geophysics by April, 1950. By mid-1949, with over half the life gone on numerous permits, many of the speculators were facing the unpleasant option of spending vast sums of money on technical evaluations such as geophysics or drilling, or losing the permits. Unwilling to spend any more money, the speculators and small explorers began to go the the "show-and-tell" route, trying to arrange farmouts to companies with the financial and technical clout to evaluate the lands properly.

It was just such a speculator who first approached Buchanan in Houston with his bag of Saskatchewan acreage. Again, seeing potential for more Leducs just east of the Alberta border, Buchanan bit the hook. The job of Harry Ross, and a newly hired geologist by the name of Earl Haines, was to mount an exploration effort on the farmins and also to acquire some permits on their own behalf. Sohio was not acting alone in this venture, for it had seven partners, namely:

8. *Ibid.*

9. Vern Hogg in interview, January 10, 1987.

10. Anonymous, "Oil in Saskatchewan," 1966, p. 52.

11. Vern Hogg in interview, January 10, 1987.

Standard Oil of Ohio Co. (the parent to Sohio Petroleum Co.);
Texas Gulf Producing Co.;
Union Sulfur and Oil Co. (Union Texas Oil Co.);
Chicago Corporation (Champlin Petroleum Co.);
Republic Natural Gas Co.;
Midstate Oil Corp; and
Bradley Producing Corp.[12]

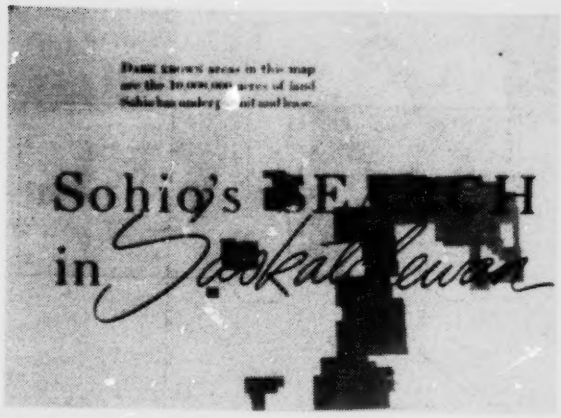


Fig. 7 This title from the October 1950 "Sohioan" feature on Saskatchewan illustrates the permit spread.
COURTESY OF BOB BISHOP.

Sohio began acting on its own in acquiring freehold and permits in April 1949. The bulk of permits filed for by Sohio was for a huge "T" centred across central Saskatchewan in an east-west direction with the base of the "T" running north-south in south-central Saskatchewan. For the most part, the permits were picked up where they could be had.

Sohio was not alone in such efforts. Tidewater Oil Co. was part of the Getty empire and was, like Sohio, a refiner, shipper, and marketer of petroleum products and not strictly an exploration company. Tidewater and its partners, the Ohio Co. (no relation to Sohio), the Atlantic Refining Co., and the Columbia Carbon Corporation, formed a joint venture known as the "Tidewater Associated Oil Company Operator" for the purpose of exploring for oil in Saskatchewan. It appears that the original entry into the Province was through farmins, for Tidewater was instrumental in changing the terms of the regulations in order to allow for an extension on time limits for its permit terms. Howard M. "Howdy" Kirk and Claude Leach were sent to Canada to head up exploration efforts on Tidewater's behalf, with Dr. R.L. Milner assigned as chief geologist.

The questions still remained: even with the permits in place, where does one begin to look? Sohio's first effort in the summer of 1949 was to conduct a vast regional gravity survey. The gravity crews took a reading at every section corner, covering almost all the permit areas by jeep, horseback, even snowshoe. The entire purpose of the survey was to determine basement configuration and detect the presence of reefs as evidenced by gravity anomalies. Sohio's second early effort was the drilling of a series of stratigraphic tests on a permit located to the northwest of Saskatoon in the Langham area. It was a beginning exploratory effort while Sohio continued to concentrate on acquiring over 10 million acres of permits and freehold in the Province.

12. Anonymous, "Sohioan," October 1950. The Sohioan has two excellent articles on the company's efforts in Saskatchewan.

The original Saskatchewan operation had been established by W.H. Strickler, a Mount Pleasant Michigan land broker, who had supervised the initial leasing; however, in 1950 Bishop and Ross were put in charge of Saskatchewan and began the work of exploration in earnest. Interest in the Sohio wells was keen as they represented the first wells of the "new wave" of exploration. Leasing continued, with the final permit, No. 137, purchased in October, 1949.

As previously mentioned, the first drilling conducted by Sohio comprised four wells drilled to the northwest of Saskatoon in the Langham area. Most of these wells were shallow tests of the Cretaceous which reached total depth at the top of the Paleozoic. One, Sohio Stratigraphic Test No. 3, reached a salt bed at the depth of 2959' which was correlated with the "Silurian" salt of southeast Saskatchewan.[13] None of the wells found hydrocarbons and all were subsequently abandoned.

Bishop and Ross were to spend the remainder of 1950 shuttling between Sohio's head office in Calgary and the newly opened office in Regina. It soon became apparent that in order to evaluate all the permits Sohio had tied up, large amounts of money, far in excess of what the original joint venturers were able to fund, were needed. Therefore, Standard of Ohio, Sohio's parent, entered into a joint venture with the original group in order to drill wells on selected partnership acreage. Another large farmout was subsequently granted to Socony Vacuum Oil in southwest Saskatchewan.

In 1950, the first wells for the definite purpose of finding oil and gas were drilled by the Sohio group. It was a new experience for some of the staff, and the field conditions were difficult, to say the least. Often, the geologist who was onsite was much more than a dispassionate observer and company representative. Bob Bishop relates this story with respect to some of the early 1950 drilling:

> *When I first drove out to Findlater in January 1950, they were down around 4000'; the rig had not been winterized and was shut down. The shale shaker was under a foot of ice and no samples had been taken for a couple of thousand feet. The geologist, Earle Haines, had been on diamond drilling holes in hard rock country but had never seen a big rig before. They had him — Earle — living in his car, chasing errands, getting no sleep, making calls, doing everything a toolpusher should have been doing. I said "Earle, you are a geologist. Your job is to make a good sample log of this well, and to do that you need to catch samples...if these people can not drill this well themselves, that is their tough luck . . .'*

The first and best prospect that Sohio had was located near the town of Plunkett. Though considered a rank wildcat, all surveys had revealed a sprawling anomaly with good closure. It looked like a hit. The well was drilled with fresh water but increased mud salinities were measured, suggesting the presence of salt. Schlumberger suggested that a new "radioactivity" log be run, and after being run, the log showed nice character, excellent definition of lime and shale beds, and potash zones within the "Silurian" salt. This tool was to prove very useful for correlation of the Mesozoic and Paleozoic strata across the Province. Later that year, in a well near Melville, the radioactivity log was again run. Bishop was quite impressed, for the logs allowed the Devonian in the Plunkett wells to be correlated with the Devonian in the Melville well. This was considered to be a major breakthrough in subsurface geology in the Province.

Tidewater was not asleep during this period. TWAO had originally picked up a large number of permits from a Montreal speculator but time was running out on them. In order to meet the work commitments, TWAO flew a large regional aeromagnetic survey over their permits. The survey

13. Technical data concerning Sohio wells have been obtained from individual well files available for examination at the Geodata Section, Saskatchewan Energy and Mines, Regina, Saskatchewan.

SOHIO PETROLEUM COMPANY
CANADIAN BRANCH
ORGANIZATION CHART
JUNE, 1951

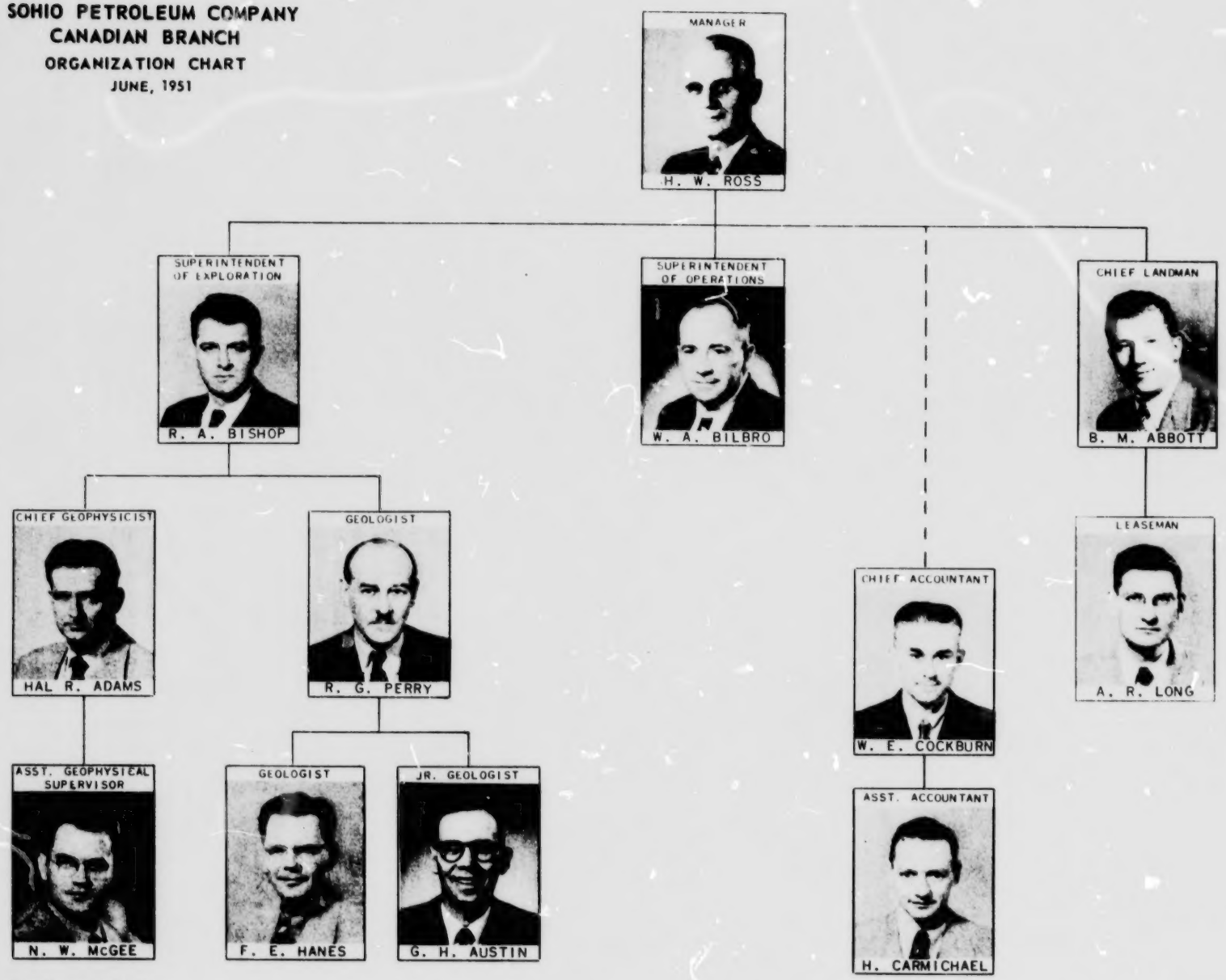


Fig. 1 The Sohio team in Saskatchewan.
COURTESY OF BOB BISHOP.

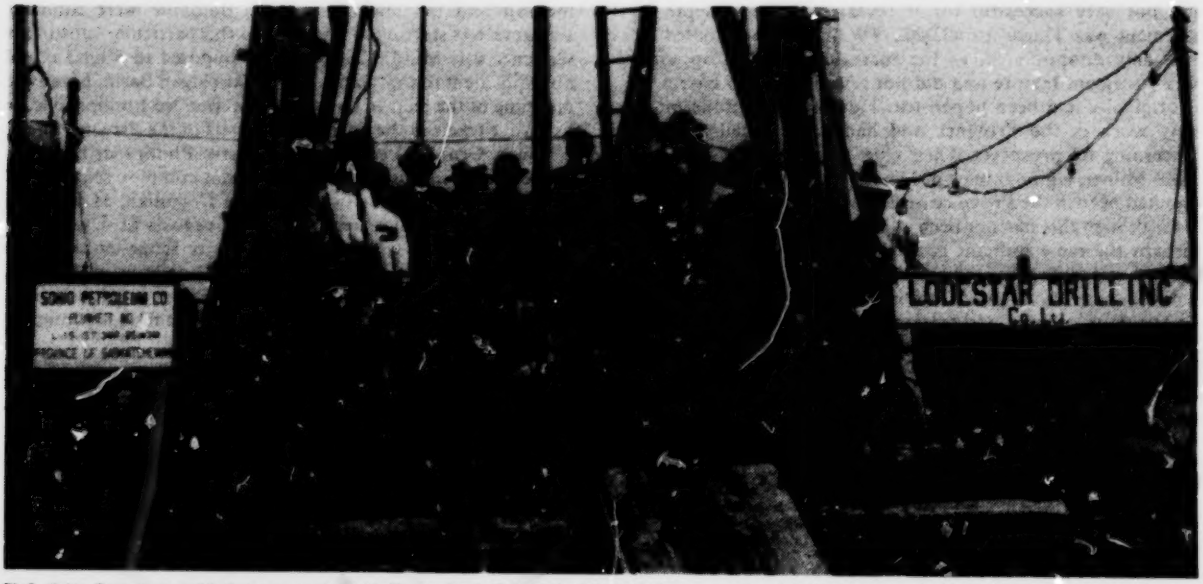


Fig.9 Sohio, Government, and Lodestar personnel at Sohio Plunkett No. 1, 15-15-14-25 W2M. Bob Bishop is second from left, Vern Hogg (seated), the late Honourable J.H. Brockelbank (on Hogg's left), and Harry Ross (on Brockelbank's left).
COURTESY OF VERN HOGG.

Fig. 10 On the rig floor, Sohio Plunkett No. 1. From left to right, Bob Bishop, Vern Hogg, Harry Ross, J.H. Brockelbank, the Honourable J.A. Darling, and Bill Bilbro (Sohio).
COURTESY OF VERN HOGG.

was not very successful for it revealed that the depth to basement was 30,000' to 40,000'. TWAO was not fooled by this, only disappointed, as the survey had picked up some intra-basement feature and did not reveal depth to basement as originally had been hoped for. Tidewater had done much early work in the Province and had some excellent ideas concerning oil prospects. Their chief geologist was Dr. R.B. (Bob) Milner, a graduate from McGill University of Montreal, who had been in the Province on Tidewater's behalf as early as 1948, though this has not been substantiated. Dr. Milner was perhaps the most brilliant geologist to have worked Saskatchewan and is largely credited with establishing a system for Jurassic correlations that is still in use today. Bob Milner was a meticulous, curious, and extremely imaginative geologist. As related to Dr. Doug Paterson of the Saskatchewan Department of Energy and Mines in a letter dated November 22, 1982, H.M. "Howdy" Kirk, general manager of the TWAO group, stated the following:

> *Without question, Bob Milner was the best geologist working in Saskatchewan in the 1950's. The Tidewater Group — who I worked for — hired some dozen or more young geologists just graduating from University. They arrived in Regina and Bob Milner would give them a six week training in sedimentation followed by some 6000' of well cuttings, and cores, for them to write up logs. This finished, they were sent out to sit on wells. They all came through good and moved to Alberta fields.*

Bob Milner spent a lot of time logging the cuttings and cores of the Norcanols wells. His exhaustive work gave him ideas and no doubt was a significant contribution to the further successes of the Tidewater Group in Saskatchewan. Of all the wildcatters, Tidewater and Sohio were perhaps the two greatest rivals, yet there was a sense of camaraderie between the two. Bob Bishop recalls logging Norcanols/Imperial core together with Bob Milner at the first core lab in Saskatoon. Though they were friends, they never shared their observations or interpretations.

The above is not to suggest that only Tidewater and Sohio were busy during 1950. Other groups were also active. Jack Porter, recently retired from Canadian Superior and one of the premier geologists of the Williston Basin of Saskatchewan and Manitoba, was with a small group called Rio Bravo during 1949 to 1950.[14] Jack was a student at the University of Saskatchewan during the war and spent his summers working with the Norcanols/Imperial Group as a field geologist mapping surface structures and sitting the occasional structure test hole. After a short stint with the Saskatchewan Department of Mineral Resources, Jack moved to Rio Bravo Oil Company and was one of the earliest Saskatchewan geologists to be based in Regina, save perhaps for Bob Milner; Rio Bravo initially became active in southwest Manitoba by participating in the Souris Valley Oil Company mapping wells in the Coulter-Lyleton area. These tests, begun in 1949, were some of the earliest deep drilling of the current boom to be punched down and involved such colourful characters as Oscar Kniseley, a promoter from Louisiana who was the main force behind Souris Valley, and Jimmie Owen, the intrepid wildcatter from Baton Rouge, Louisiana.

Jack also was involved in field work conducted along the shores of Lake Winnipegosis, Manitoba, in 1949. This work was done in conjunction with geologists from Hudson's Bay and Phillips, who were also convinced that the best propects to pursue in Saskatchewan were the Winnipegosis reefs that might offer similar oil and gas possibilities as those found in the Alberta subsurface. McGehee (1949)[15] was one of the first to dispel the belief commonly held by industry geologists that the salt and the underlying basal dolomite were Silurian. Evidence was starting to suggest that this particular subsurface sequence was Middle Devonian, as opposed to Silurian, and not equivalent to the "Salina" of the Michigan Basin. Extensive mapping of the reefs in the outcrop section led Phillips to lease extensive tracts in the north-central part of the Province in the Nipawin/Gronlid/Peesane areas. Early Phillips drilling was concentrated in this area and revealed a complex sequence of reef/off-reef sequences in the Middle Devonian, as well as a show of oil-cut mud from the Winnipegosis in a well near Gronlid. Phillips was not limited in its scope of thinking: besides chasing the reefs, Phillips was also active in the west-central portion of the Province where oil had previously been found. It concentrated on the region south of the Lloydminster heavy oils in the Eatonia/Driver area.

Also active in the central Saskatchewan reef hunt was Britalta Petroleums Ltd. Britalta drilled a number of deep tests on its permits held largely north and east of Saskatoon. Wells such as Pelican Lake, Rosthern, and Carpenter were drilled; however, all were dry and abandoned.

Other explorers were sticking to the less rank wildcat areas of the Province. In the summer of 1950, Albercan Oil Corp. made a discovery of heavy "Black" oil at Heart's Hill in west-central Saskatchewan. The well, Albercan's Heart's Hill No. 1, 2-22-35-26 W3M, discovered a show of heavy oil in the Lower Mannville but the discovery was deemed small and uneconomical. This well did establish the presence of oil away from the Lloydminster area and was thus an encouragement to explorers.

THE MISSISSIPPIAN OF SOUTHEAST SASKATCHEWAN

It is interesting to note that the Mississippian subcrop play of southeast Saskatchewan was largely ignored by many of the early wildcatters. There were those, however, who were not that casual about the potential of the area, for the first part of the Province that the majors moved into was the southeast. Imperial and, to a certain degree, Shell began extensive leasing programs of freehold lands in the southeast. The reason for this, as previously stated, was that the majors, especially Imperial, did not trust the socialist C.C.F. government of Tommy Douglas and would rather deal with individuals as opposed to governments. The wildcatters had flocked the Crown permit areas, seeing this strategy as a way of obtaining a large land position without too much administrative complexity and cost. The majors could easily handle several thousand individual freehold leases; a speculator, and the outsider that the speculator flipped to, could not. Some companies, notably California Standard Ltd., spent considerable energies within restricted areas. In the late 1940s, Calstan began an extensive program of freehold leasing, regional seismic, and surface mapping in southwest Manitoba. Also active in southwest Manitoba were various promoters, such as the previously named Oscar Kniseley.

One company that followed the majors' philosophy in southeast Saskatchewan and southwest Manitoba was Rio Bravo Oils Ltd., later to become Canadian Superior Oil Ltd. Rio Bravo was the exploration arm of the large Superior Oil Company of the United States. The young Jack Porter guided Rio Bravo's efforts in the Province and was among the first to recognize the potential of the Mississippian subcrop. Key to Rio's subsequent success in the southeast and in Manitoba was its participation in the early Souris Valley deep tests drilled by Souris Valley Oils Ltd. in 1949. These wells established that the thick sequence of Mississippian rocks found in the

14. Vern Hogg in interview, March 4, 1987.

15. J.R. McGehee, 1949, "Pre-Waterways Paleozoic Stratigraphy of Alberta Plains" in "Western Canada Sedimentary Basin," Rutherford Memorial Volume, Amer. Assoc. Petrol. Geol., 1954, p. 131-142.

The Williston Basin Nomenclature Committee of the American Society of Petroleum Geologists met in Bismarck on February 18. The group arrived at many decisions regarding the nomenclature of rock strata of various geological ages. The work of this committee will go before the national committee on nomenclature of the A.A.P.G. at the March meeting in Houston. Decisions will be announced in the Petroleum Geologists Bulletin soon after the national meeting.

Left to right, standing are: J. W. Porter, Canadian Superior of California, Regina; R. A. Bishop, Sohio Oil, Regina; Rod Tetrick, Socony-Vacuum, Pegasus Division, Bismarck; C. A. Barkell, Shell Oil, Casper; Herb Hadley, Billings Geological Service, Billings; Mike S. Stanton, California Standard, Winnipeg; R. L. Milnor, Tide Water Associated Oil, Regina; seated: George Summers, Jr., Smith and Summers, Bismarck; A. V. Martini, California Company, Bismarck; Alex Clark, Chairman of the Coordinating Committee, President of the Rocky Mountain Section of the American Association of Petroleum Geologists, Williston Oil and Gas, Casper; Raen de Witt, Sohio, Regina; and A. J. Goodman, Socony-Vacuum, Pegasus Division, Calgary.

Fig. 11 Several of the premier Saskatchewan geologists were members of the Williston Basin Nomenclature Committee and were instrumental in defining the subsurface stratigraphy of the Canadian portion of the Williston Basin.
COURTESY OF THE SASKATCHEWAN GEOLOGICAL SOCIETY.

subsurface of the southernmost portions of the two Provinces pinched out due to erosion to the north. This suggested a large stratigraphic trap which may have trapped oil at the subcrop. The potential was recognized by the majors as well as by the government workers, such as Dr. Lillian Kerr of the Manitoba Department of Mines.[16] The second reason for the eventual success of Rio Bravo lay in the freehold leases. Rio Bravo began an extensive leasing program of freehold lands in a checkerboard pattern throughout the southeast Saskatchewan and southwest Manitoba. This early leasing was to provide Rio Bravo and Canadian Superior with a tremendous advantage when oil was discovered on offsetting leases owned by competitors.

In 1951, a substantial oil strike occurred. California Standard discovered 32° gravity oil at Daly, Manitoba in January of 1951. The California Standard Daly 15-18-10-27 WPM well was spudded on November 16, 1950, and was completed on January 19, 1951. Drillstem tests recovered rather poor oil shows in the Mississippian (the best test recovered 105' of flocculated mud, gas-cut with spots of brown oil, over the Mississippian Lodgepole Formation). Better shows in the wildcat areas of Saskatchewan were being ignored; however, Calstan ran pipe and completed the well. An openhole completion was attempted from 2200' to 2340', and some oil was obtained. The well did not prove to be economical, yet Calston did not give up, drilling Daly 10-18 in February 1951 and Daly Province 7-12 in an attempt to define the oil accumulation. These efforts by Calstan showed its fortitude and perseverance in the hunt for hydrocarbons in the Canadian portion of the Williston Basin.

The Daly discovery was actually earlier than the discovery of oil in the Amerada Beaverlodge well of North Dakota, though the Beaverlodge well was spudded earlier. The Amerada well established production from the Devonian and was ultimately to open up the tremendous production from the Nesson Anticline, a major structural feature found in northwest North Dakota. Shell was also successful in the Williston Basin, finding oil at Richey, Montana in July of 1951. It seemed at this time that the best production might be found in the southeast of Saskatchewan and the southwest of Manitoba primarily in the Mississippian and Devonian. Perhaps there was little correlation between the prolific hydrocarbon-bearing reefs of Alberta and those hunted in central Saskatchewan, but the explorers and wildcatters were not about to give up yet. Despite this fact, southeast Saskatchewan did not see the rush of wildcatting that occurred in central and southwest Saskatchewan until the discovery of Midale and other subcrop fields in 1953. Some explorers were successful, notably the TWAO

16. Memos found in Petroleum Branch well files available for inspection at Manitoba Department of Energy and Mines, Winnipeg, Manitoba.

group at Wapella in October of 1952. The oil reservoir was found to be within the Lower Cretaceous "Wapella" or "Basal Quartz" sand with the structure well defined on seismic. This emphasis on the Cretaceous and Jurassic was not surprising, for in February of 1952 the Socony-Western Prairie group discovered oil at Fosterton in southwest Saskatchewan. Minds began to realize the Jurassic/Lower Cretaceous sequence to have the greatest immediate potential for oil production.

SOUTHWEST SASKATCHEWAN

Early drilling had been conducted in the extreme southwest of the Province by Imperial, which drilled its Boundary No. 1 well at 4-8-1-27 W3M in 1916. This well was targeted to evaluate a large regional fault system that was mappable on the surface. Unfortunately, the structure was the result of thrusting induced by the Tertiary uplift and igneous activity in the Sweetgrass and Bearpaw Hills area to the south in Montana, and was to prove barren.[17] Marland Oil Ltd. had also conducted early exploration in the Eastend area in 1924 and 1925 but its wells were also dry. It is difficult to determine at this point in the story whether the early explorers had any indication of the subsurface Swift Current Platform and shelf; probably what guided exploration efforts were the large surface structures visible in the Tertiary and Upper Cretaceous sequences.

An interesting well was drilled by an early Saskatchewan oil pioneer at Fox Valley (Lsd 16-26-17-26 W3M) in 1946.[18] The well established the presence of gas reserves in what is now Saskatchewan's largest gas field, namely Hatton-Horsham. The driller of the well was a former securities salesman by the name of Tom Keyes, who picked up exploration permits guided by reconnaissance work conducted by a certain George Paul D'Aigneaux. D'Aigneaux claimed to be able to detect oil and gas at depth using certain black box methods of measuring radioactive emanations. Though dismissed as a "doddle-bugger" and "quack," D'Aigneaux outlined the Hatton-Horsham-Fox Valley and the Dollard areas as being prospective for oil and gas. Despite what one may think of his methods, the two areas were to prove to be major producing areas in the Province. Unfortunately, due to a series of financial setbacks and a dispute with the C.C.F. government, Keyes lost his permits and, along with them, the prospect of being the father of the modern petroleum industry in the Province.

The most active explorers in the southwest included the Socony-Western Prairie group, Woodley Petroleums, Alber-can-Canadian Southern, Phillips (further to the north),and the TWAO group. Phillips was rewarded with some oil up near Eatonia; however, the premier big strike was made by Royalite and Canada Southern at Buffalo Coulee/Coleville in August of 1951. The pool produced oil and gas from the Viking and the "Banff" (the Mississippian Bakken) and was found by a combination of seismic and subsurface mapping. This was a new play concept as the main trapping mechanism was the presence of paleotopographic erosional remnants of Mississippian Lodgepole and Bakken surrounded by detrital and shaly sediments.

Buoyed by this success, exploration heated up and eventually led to the discovery of oil at Fosterton by the Socony-Western Prairie Group in December, 1951. Socony Western Prairie Fosterton No. 1 (Lsd 2-10-17-18 W3M) was the discovery well for the Fosterton pool. This oil strike led to an eruption of exploration in the area. Some operators, such as the TWAO group, were extremely active throughout southwest Saskatchewan, so much so that Bob Milner was able to use only his TWAO wells when illustrating his pioneer work on the Jurassic stratigraphy of Saskatchewan.[19] These discoveries led to a concentration of interest upon the Cretaceous and the Jurassic in the southwest, possibly at the expense of the Mississippian in the southeast. Wapella, a Jurassic-Lower Cretaceous field in the southeast, also led to extensive Mesozoic tests in this portion of Saskatchewan, most notably in the area north of the main Mississippian producing trend.

The above is a brief, and by no means complete, history of the earliest days of the exploration boom in Saskatchewan. Perhaps we should now pause and ask the question: What were these explorers thinking and what did they find? Let us look as some of the conundrums uncovered by the early explorers.

"BUCKET OF GUTS"

The problems and confusions facing the early explorers after their initial spate of exploration drilling can be summed up in the following categories:

- the nature and presence or absence of the Prairie Evaporite salt and the bizarre structures associated with its distribution;
- confusion in stratigraphic correlation;
- numerous and apparently discontinuous carbonate porosities;
- problems in seismic correlations and interpretation;
- basin configuration; and
- subsurface fluid flow.

I will examine two of the most pressing problems: salt solution and seismic exploration.

THE PRAIRIE EVAPORITE AND SALT SOLUTION

As discussed previously, the early explorers believed that the deep salt section found by early Norcanols/Imperial wells was Silurian in age and could be roughly correlated with the Salina of the Michigan Basin. The fact that salt was found in some areas of the Province and not in others had led Imperial to believe that the salt was deposited in isolated pans or basins, not as a regionally extensive layer. The early drilling was to reveal a radically different interpretation.

I am about to enter into a controversial area of discussion: who first uncovered the concept of salt solution? To this day, battle lines are drawn between those who say Bob Milner of TWAO was the first, and those who claim it was Bob Bishop of Sohio. I am not about to make any judgement as to who was first, but rather will look at Bob Bishop's experiences with salt solution. Bishop was the first to publish his views concerning the theory of salt-collapse, most notably in his papers of 1953 and 1954[20], though Bob Milner did present an abstract concerning salt collapse in the First Williston Basin Symposium published in 1956.[21] The following passages are based on Bishop's recollections concerning salt collapses.

17. Jack Porter in interview, March 4, 1987.

18. Nordahl Flakstad, "Drilling Deep for Oil and Justice," Regina Leader-Post, Saturday, August 24, 1985, p. B2.

19. R.L. Milner, and G.W. Blakslee, 1956, "Notes on the Jurassic of southwestern Saskatchewan." In "Jurassic and Carboniferous of Western Canada," John Andrew Allan Memorial Volume, Amer. Assoc. Petrol. Geol., 1958, p. 65-84. See especially cross-section D-E, p. 74.

20. R.A. Bishop, 1954, "Saskatchewan exploratory progress and problems." In "Western Canada Sedimentary Basin," Rutherford Memorial Volume, Amer. Assoc. Petrol. Geol., 1954, p. 475-485 (from private reprint). Paper originally presented at a meeting of the Saskatchewan Geological Society of October 8,1952. Also R.A. Bishop, 1953, "Saskatchewan exploratory progress and problems," Alta. Soc. of Petrol. Geol. News Bull. v. 1, no. 8 (August), p. 3-6 (Digest by R.T.D. Wickenden and Leon Price). Also in "Canadian Oil and Gas Industries," July 1954, p. 37-42 (Digest by R.T.D. Wickenden and Leon Price).

21. R.L. Milner, 1956, "Effects of salt solution in Saskatchewan," (abstract), First Williston Basin Symposium, p. 111.

In October of 1952, Bob Bishop read a paper before the Saskatchewan Geological Society stating that some of the structures found in the subsurface of Saskatchewan may have been caused by the removal of the Prairie Evaporite salts. It was a bold paper to present, as the nature and extent of these salts was still very controversial; however, Bob was a confident fellow and thought it best to go with what he had. The paper was well received and remains the best summary of what was known about the Saskatchewan subsurface at that time. Sohio had drilled numerous wells on large sprawling structures and seismic closures, but all were dry. The Sohio team had nicknamed the structures they were mapping "Bucket of Guts" structures because these features seemed to wind and weave over a large area and displayed poorly defined lateral edges. These features also displayed a dendritic pattern as opposed to discrete closures. Bishop was not sure if they represented erosional relief structures or if they might not be reefs due to the absence of structure at deeper horizons.

What led to salt collapse as a mechanism for structural development? Bishop noted several interesting points. If a full section of salt was encountered, the contours of overlying formations described a gently dipping surface mirroring the Williston Basin. If the salt was absent, anomalously low areas were present. Never were anomalously high areas found in conjunction with the absence of salt. Also, gamma ray logs enabled the correlation of salt beds over wide areas, and mapping of these beds revealed some regions where the upper portion of the salt was missing. Salt flowage and normal faulting were considered; however, the evidence for this was absent, again due to the lack of anomalously high areas. Finally, the "Bucket of Guts" structures showing a dendritic pattern pointed to some form of paleodrainage, as opposed to deeper tectonic influences.

Mapping in the central portions of Saskatchewan revealed a widespread "zone of steep dips" coinciding with the postulated edge of the salt deposits. The theory that the structures represented paleotopography was also soon discounted when drilling revealed that there was no appreciable thinning of sediments overlying the structures; rather, drape was observed, suggesting that these structures were formed after the deposition of overlying beds.

Bishop had always been keenly interested in evaporites, and in 1949 attended a talk in Calgary given by Mr. Paul Weaver of Gulf Oil dealing with the formation of evaporite basins. He read all he could concerning evaporites, their precipitation, and flowage. A paper in the 1952 edition of "Geophysics" described the formation of sinkholes in Kansas due to the removal of underlying salts. If salt removal created shallow, recent holes, could not the solution of the deep salts have created the observed anomalies in Saskatchewan? There it was, the proverbial flash of lightning.

The real evidence that Bob Bishop was looking for was found while Sohio was drilling near Venn, Saskatchewan. In the words of Bob Bishop:

> *Sohio was drilling with as many as five drilling rigs and eleven seismic crews, counting the double-shift crews, and we were busy!...C.B. Smith, geophysicist on loan to us from Sohio's Oklahoma City office, was attempting to supervise all the seismic crews, and he described what looked like an oval-shaped structure which was building at Venn. He then left to go visit the crews. A couple of hours later Harry Ross came in to my office and said "We have a rig ready to move. Where do you want it to go? I said, "Well, we are still shooting at Venn, but a pretty fair structure is building on Line so-and-so. Let's drill there'.' Three days later, Smitty came back and I told him what I had done. He was quite upset and said "But that is just a hanging line. It is not tied to anything! We are not finished there!" I answered, "That's tough. We're rigging up right now!" Well, Smitty's concerns were justified; the Venn anomaly had a dent in it, and we drilled the well in the dent*[22].

Sohio Venn No. 1, located at 15-16-29-14 W2M, was drilled in September and October of 1950. It came in low and, most importantly, lacked salt. The rig was moved to 4-28-29-24 W2M, and found the tops to be running high as well as encountering a full section of salt. This well was also dry. Sohio left bad enough alone and abandoned the prospect. In 1952, Consolidated Allenbee approached Sohio and wanted to drill a prospect, "any prospect".

The Venn structure had an untested lobe on the other side of the dent, and in June of 1952 a well was spudded on the untested lobe. Again, tops were high with a full salt section present. This prospect was key to Bishop's understanding of salt structures and is illustrated in his papers. Bishop's theory grew from the results of field observations from widely scattered exploratory wells and as such was not comprehensive enough to describe all the aspects of the phenomenon. Bishop was a firm believer of single (as opposed to multi-stage) salt collapse structures, and never tried to examine possible positive elements of the features.

Salt collapse made for an interesting talk, and Bishop won the A.S.P.G. Medal of Merit for the best paper presented during 1952. Not all, however, subscribed to his theory. He was to find out that salt collapse was an anathema to geologists in certain organizations, such as Socony, who were "practically forbidden by their management to even talk about such a wild theory". Imperial also felt that salt collapse was not viable, believing instead in depositional controls upon salt distribution.

Bob Milner was a believer in salt collapse. His abstract entitled "Effects of Salt Solution in Saskatchewan"[23] described his theory, which was similar to Bishop's except for Milner's recognition of multiple events and the flowage of subsurface waters. He also stated that the Prairie Evaporites are being removed at the present day, thereby giving the phenomenon a dynamic aspect.

Despite the controversy over the theory's first proponent, salt solution was poorly understood until the mid-1960s. It wasn't until the discovery of oil in the Upper Devonian Birdbear Formation trapped within a multi-stage structure caused by salt collapse at Hummingbird in 1966 that it became apparent salt collapse might form favourable traps for hydrocarbons. Previously, explorers were more concerned with the regional structural aspects of salt solution. One wonders whether all the old wildcats drilled on the obvious seismic features were drilled in the most prospective portion of the salt collapse structures, and whether or not viable plays may yet exist in these "barren" features.

SEISMIC PROBLEMS

The early explorers conducted regional seismic shooting with a shot taken every mile or quarter-mile. Detailed correlation and grid shooting were conducted only over large structures defined by the reconnaissance shooting. This was simply a matter of expediency, for the huge scale of permits and the need to define them quickly and cheaply were paramount. An example of such a program is detailed in a memo dated October 6, 1954 submitted by TWAO to the Department of Energy and Mines. This memo concerns shooting near Dundurn that was conducted from 1950 to 1952 over 3 permits having a total area of 167,840 acres. Some 359 miles of continuous profiling was done on the Blocks. Computations were made "in the normal manner," meaning the use of up-hole times for near surface corrections and the referencing of data to a horizontal reference plane using a

22. Bob Bishop, written communication, 1987.

23. R.L. Milner, 1956.

correction velocity of 6000' per second. The corrected times were converted to depths using a time-depth chart. The velocities were relatively low (7000' to 8000'/sec) through the Cretaceous and considerably higher through the Paleozoic rocks. The chief reflecting horizons were the top of the Paleozoic and the top of the Lower Devonian. Unfortunately, in some areas, the only reliable reflector was the top of the Paleozoic, because lower reflectors were masked by "ground roll". There parameters were consistently used by other operators, and the generated seismic records are, at best, of only fair quality in terms of supporting valid interpretations.

Further problems in seismic acquisition and interpretation were revealed in the paper by Reasoner and Hunt published in 1952 on the Coleville-Buffalo Coulee oil pools.[24] A seismic survey conducted by the Independent Exploration Company revealed a structure which was drilled by Royalite and Canada Southern Oils Ltd. in 1951. Reasoner and Hunt stated that "direct seismic contouring, based on present methods of computation, cannot be used on horizons below the erosional surface because of velocity changes at the surface". Variations between the high-velocity buried hills and the lower velocity infilled valleys caused the lower reflectors to mirror the structure of the buried topography. Furthermore, they state:

> *Many wells have been located throughout Saskatchewan on seismic "highs" which had been interpreted as Paleozoic structures and when drilled proved nothing more than the presence of buried limestone hills.*

Needless to say, seismic techniques and the knowledge of the stratigraphy of the subsurface were very poorly understood in the late 1940s and early 1950s. One can only guess at what was revealed in these early seismic programs, and no doubt many wildcat wells presented surprises. When the intricacies of salt removal tectonics and ensuing structural development are coupled with difficult detection methods, it is amazing that oil was found at all.

FACING FORWARD BUT LOOKING BACK

A paper such as this cannot even begin to do justice to this fascinating story. Even after 35 years, all of those I talked to still became excited and animated when this first exploration is discussed. It was an exciting, intellectually challenging, and competitive period to be practising geology. The early geologists were truly frontier explorationists, excellent geologists (they had to be), and quite bold. Now to ask the final question: Can we, as practising geologists in Saskatchewan, learn anything from these early efforts?

I believe that we can. Perhaps the age of frontier geologists is not over. Presently in the Province of Saskatchewan, oil is produced from four primary areas: the Mississippian subcrop in southeast Saskatchewan, the Jurassic and Cretaceous of the Swift Current Platform in southwest Saskatchewan, the Viking/Bakken pools of west-central Saskatchewan, and the Cretaceous heavy oils of the Lloydminster area. Lying like a huge circular wasteland in the centre of the Province is a vast region that has been drilled by three distinct groups: the early wildcatters, potash exploration companies, and the Winnipegosis Pheasant and related "Keg River" programs of the mid- to late-1960s.

One can make the generality that in each of the four producing regions, the habitat of oil and natural gas is unique to that particular area. Each region has its own unique play concepts and reservoir characteristics, leading to the specialization of geologists working the Province. In the barren central portion of Saskatchewan, explorers have looked for subcrop plays, Jurassic and Cretaceous shelf trends, Paleozoic reefs, and large tectonic structures; however, all these play concepts have met with failure. One could argue that either the area is geochemically immature and has thus never generated oils, or it has been flushed by meteoric waters moving from Montana in a northeasterly direction to the outcrop belt of eastern Saskatchewan and western Manitoba. Yet oil shows have been recorded in wells in this region, indicating that these precepts may not be entirely correct. Perhaps we are dealing with a different type of beast in this region.

The key concept which requires re-evaluation by present-day explorers is the theory of salt solution. In central Saskatchewan, as opposed to the southeast, southwest, or west, complex and multi-stage salt removal events have led to the creation of large structural trends in formations overlying the salt. Salt solution has been the primary geological process shaping the structural pattern and may have had a dynamic effect upon the deposition of the sedmiments themselves. The early explorers were able to map these various features with their imprecise tools, and drilled their wells to evaluate the highest portions of these features, not necessarily the best trapping configuration or potential reservoir. The early explorers were also unsure of the implications of multi-stage salt collapse structures, preferring to interpret the results of salt solution as single-stage structural creations. Considering the wealth of data presently available concerning oil production from salt solution structures and the availability of modern seismic methods, the re-evaluation of regional salt removal regimes may be interesting.

Regional fluid flow and flushing also may not be as difficult to assess as was previously thought, in that modern techniques of fluid geochemical analysis may be able to define separate flushing regimes or areas where the lower salinity may not be due to meteoric water infiltration. As witnessed in this paper, early formation-evaluation techniques were not what they are now, and many of the early tests must be considered suspect. Regional carrier porosities may allow the wholesale flushing of a particular zone, but one must ask the question whether indeed such regional carrier porosities exist.

The title of this paper states "New Oil from Old Ideas". Understanding our predecessors' ideas will greatly aid any re-evaluation of an area. As George Santayana stated: "Those who cannot remember the past are condemned to repeat it".[25]

ACKNOWLEDGEMENTS

This paper could not have written without the assistance provided by C.A.L. (Vern) Hogg, Dave Francis, Don Stewart, Bob Bishop, Roger Edmunds, and Jack Porter, in the form of written notes and taped conversations. Others active in the early oilpatch also provided valuable insights but have not yet had their chance to speak on tape. Dr. Doug Paterson, Saskatchewan Energy and Mines, Regina, kindly allowed access to early Saskatchewan Geological Society records and files. My thanks also go to Bob Bishop of Lakewood, Colorado: Vern Hogg of Calgary, Alberta: and Imperial Oil Limited of Toronto, Ontario, for kindly providing the photographs. Molly Nichol is graciously thanked for her editing, typing of the final draft, and suggestions concerning the preparation of historical papers. Finally, I thank the Symposium Committee of the Fifth International Williston Basin Symposium for financial assistance towards the preparation of this paper, which represents part of an ongoing project to record and preserve the memories, experiences, ideas, and dreams of the early oil explorers in Saskatchewan who must be considered the true authors of this chronicle.

24. M.A. Reasoner and A.D. Hunt, 1956, "Structure of Coleville-Buffalo Coulee Area, Saskatchewan", in "Jurassic and Carboniferous of Western Canada," John Andrew Allan Memorial Volume, Amer. Assoc. Petrol Geol., 1958, p.391-405.

25. George Santayana, *Reason in Common Sense*.

FACTORS DETERMINING THE THERMAL HISTORY OF A CONTINENTAL BASIN

WILLIAM D. GOSNOLD, JR. AND
YUE CHAIN HUANG

Geology Department
University of North Dakota
Grand Forks, ND 58202

ABSTRACT

Thermal conductivity and heat flow control temperatures within a basin. Knowledge of thermal conductivity and variations of thermal conductivity and heat flow with time are, therefore, critical factors in determining a basin's thermal evolution. A model for thermal evolution of the Williston Basin serves as a typical example of the effects of thermal conductivity structure and variation in thermal conductivity with time.

The thermal conductivity of the Williston Basin can be divided into a high-conductivity, Paleozoic carbonate section and a low-conductivity, Mesozoic and Cenozoic clastic section. This structure causes a geothermal gradient profile that essentially has two components. A gradient of about 50 K km^{-1} characterizes the clastic rocks and a gradient of about 20 K km^{-1} characterizes the carbonates. The marked vertical variation in geothermal gradient structure precludes use of bottom-hole temperature data for estimating the thermal history of strata in the basin. Variation in sediment thermal conductivity in time is one-directional and is significantly influenced by sedimentation rate, compaction rate, sediment composition and sediment thickness. Thermal conductivity of Mesozoic and Cenozoic clastic sediments in the basin increased by about 30 per cent due to compaction during sedimentation. This time-variation in conductivity caused a gradual reduction in subsurface temperatures by about 20 degrees Celsius in the primary oil source rock, the Bakken Formation, during the early Tertiary. Application of a two-dimensional thermal model that includes variable thermal properties predicts a significantly different thermal maturity for the basin than does a simple model based on present geothermal gradients.

INTRODUCTION

The thermal evolution of sedimentary basins has received increased attention from the petroleum industry since Waples's (1980) discussion of Lopatin's (1971) method for predicting thermal maturity. In concept, the thermal maturity of petroleum source rocks should be calculable if one can accurately determine the temperature profile for the source rock through time. A number of workers have approached this problem by using present day geothermal gradients to determine paleotemperatures (Lopatin, 1971; Waples, 1980; Schmoker and Hester, 1984; Price et al, 1984). Other workers have proposed thermo-mechanical models for basin formation and have projected basin temperatures as a function of the subsidence rate and the decrease in heat flow that drives the model (McKenzie, 1978; Turcotte and Ahern, 1977; Haxby et al, 1976; Ahern and Mrkvicka, 1984; Nunn et al, 1984; Garner and Turcotte, 1984).

Each of these approaches has provided insight into important aspects of the thermal evolution of sedimentary basins. However, in some cases these models produce conflicting results. For example, several workers have based estimates of the thermal maturity of the Bakken Formation in the Williston Basin on temperature gradients derived from bottom-hole temperatures (Webster, 1984; Schmoker and Hester, 1984). Their estimates conflict with interpretations of geochemical data by Price et al (1984) who suggest that the Bakken has reached thermal maturity levels that exceed those predicted using estimates of present-day basin temperatures.

A fundamental problem in this type of analysis is obtaining a valid estimate of present-day temperatures. The common technique for analysing basin temperatures, projecting linear temperature gradients based on bottom-hole temperatures of oil wells, has been applied to the Williston Basin by Nixon (1973) and Meissner (1978) and has been used for paleotemperature estimates by Webster (1984) and Price et al (1984). The temperature gradients used in these estimates are on the order of 34°C km^{-1}. However, equilibrium temperature gradients measured with thermistor probes reveal a complex temperature gradient profile that is non-linear and, in a single profile, may range from 60°C to 20°C km^{-1} (Gosnold, 1985).

Another fundamental problem arises from using present-day temperatures as paleotemperatures. This problem has been recognized for the Williston Basin by Price et al (1984) whose geochemical data indicate significantly higher paleotemperatures than would obtain from the present-day temperature gradients given by Meissner (1978). Another example of differences between present and past basin temperatures was given by Naeser (1985) who compared fission-track closing temperatures to present-day geothermal gradient data and suggested that several Tertiary basins in the western United States had significantly higher temperature gradients in the past.

We address these problems in modeling a basin's thermal history by analysing the factors that control present and past temperature profiles. In particular, it will be shown below that the assumption that linear temperature gradients can be used to estimate basin temperatures may be invalid in the general case and is particularly inappropriate for the Williston Basin. We also examine the assumption that present-day gradients may be used to determine paleotemperatures and suggest explanations for inferences of high paleotemperatures in some basins. The essential elements of our approach were discussed by Sclater and Christie (1980) as applied to the North Sea; however it appears that their work has not been considered by subsequent workers in continental basins.

FACTORS THAT CONTROL SUBSURFACE TEMPERATURES

Quantitative analysis of the thermal structure of the subsurface requires determination of several thermal properties of the strata and the local heat flow. In the simplest case,

application of Fourier's law of heat conduction would allow determination of subsurface temperature by

$$Q = dT/dZ * k \qquad \textbf{Equation 1}$$

where Q is heat flow in mW m^{-2}, k is thermal conductivity in W m^{-1} K^{-1}, dT is the increment of temperature change in a vertical length, dZ. The temperature at any point, Z, can be calculated by

$$T = T_0 - \sum_{i=1}^{n} Z_i (Q/k_i) \qquad \textbf{Equation 2}$$

where T_0 is surface temperature, Q is the conductive heat flow, Z_i is the depth of the i^{th} layer, and k_i is the conductivity of the i^{th} layer.

The gross thermal conductivity structure of the subsurface in the Williston Basin comprises two distinct components: a high-conductivity Paleozoic carbonate section and a low-conductivity Mesozoic and Cenozoic clastic section. For normal continental heat-flow values of about 60 mW m^{-2}, a gradient of about 50 K km^{-1} would characterize the clastic rocks and a gradient of about 20 K km^{-1} would characterize the carbonates (Fig. 1).

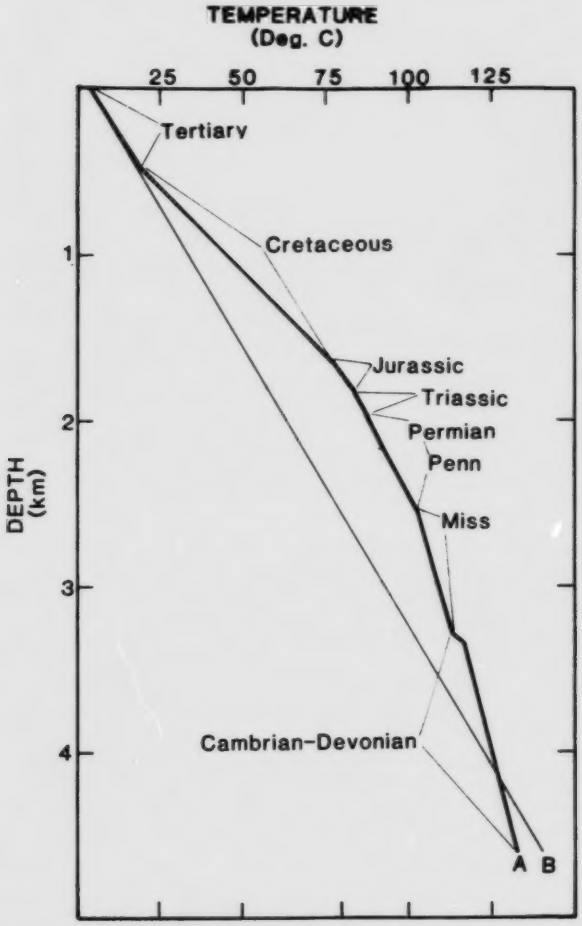


Fig. 1 Temperature versus depth plots for the Williston Basin. Curve A is a composite based on four deep temperature logs of the basin using equipment designed for heat-flow studies. The curve shows high temperature gradients in the upper, clastic section of the basin and low temperature gradients in the lower, carbonate section of the basin. The temperature gradient is inversely proportional to the thermal conductivity. Curve B is a linear temperature gradient that would be calculated using an accurate temperature measurement where curve B crosses curve A.

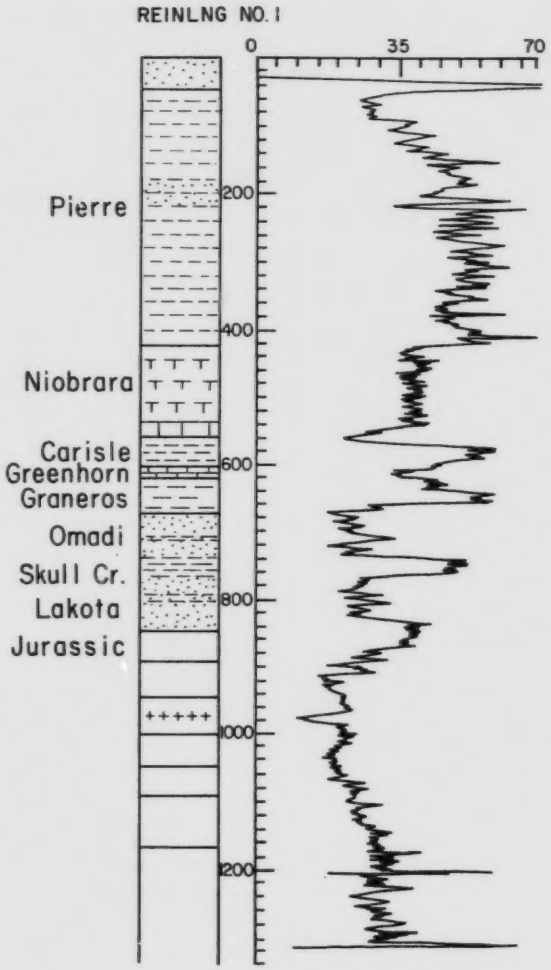


Fig. 2 Gradient versus depth and stratigraphy for a well in the Denver Basin in western Nebraska. Depths are in metres and gradients are in K km^{-1}. The temperature log was made with a continuously recording heat-flow probe. Because the temperature gradient is inversely proportional to the thermal conductivity, the gradient versus depth plot shows changes in conductivity which suggest changes in lithology.

The data necessary to characterize the present thermal structure in a sedimentary basin according to Equation 2 are heat flow, formation conductivities, formation thicknesses and heat flow.

THERMAL CONDUCTIVITIES

The question of thermal conductivity is critical. Each lithologic unit has a characteristic thermal conductivity due to differences in composition, grain size, and porosity. All three factors cause differences in conductivity among strata, and the effects on the geothermal gradient may be observed with precision temperature logs (Fig. 2). Except for shales and silts, thermal conductivities of rocks are easily measured in the laboratory. However, these measurements give present conductivities and it is critical in thermal history analyses to consider variations in conductivity with time. Composition is

fixed in time but grain size in carbonates and evaporites and porosity in most rocks can change due to compaction and cementation. In particular, the porosity of sediments tends to decrease with degree of compaction, which commonly corresponds with geologic age, and tends to cause an increase in thermal conductivity with age. This increase is analogous to increases observed in density and seismic velocity in sedimentary units with increasing age and depth.

In a gross sense, the lithology of the Williston Basin can be divided into an upper, clastic section and a lower, carbonate section. This lithologic division gives a two-component thermal conductivity structure to the basin which can be characterized by calculating effective thermal conductivities as

$$E.C. = \sum_{i=1}^{n} \frac{L_i}{k_i} \qquad \textbf{Equation 3}$$

where L_i is the thickness of the i^{th} layer and k_i is the conductivity of the i^{th} layer.

Shales dominate the clastic section. However, shale conductivities are particularly difficult to measure in the laboratory because shales are too soft for measurement of cores in a divided bar apparatus and their anisotropic nature causes a bias toward high values when using the chip method (Sass et al, 1971; Blackwell and Steele, 1981).

The general problem of thermal conductivities of shales was criticially examined by Blackwell and Steele (1981) after they observed discrepencies in interval heat flows for alternating limestone and shale layers in Paleozoic rocks in Kansas. Consequently Blackwell and Steele (1981) suggested that previous measurements of shale conductivities were about 40 to 50 per cent high and should be reduced from 1.7 W m^{-1} K^{-1} to about 1.1 W m^{-1} K^{-1}. Sass and Galanis (1983) made thermal conductivity measurements on core samples of the Pierre Shale from a well near Pierre, South Dakota, using a needle probe oriented both radially and axially. Their reported value of 1.2 W m^{-1} K^{-1} agrees with the shale estimates of Blackwell and Steele (1981). Consequently a range of shale conductivities of 1.1 to 1.2 W m^{-1} K^{-1} was adopted for this study.

Thermal conductivities of carbonates and sandstones in the subsurface are better known because samples can be measured relatively easily. These conductivity values are compiled in a general thermal conductivity scheme for the stratigraphic section in the Williston Basin in Table 1.

For the general case where the thermal conductivity structure of the Williston Basin is divided into two components, the upper, shale section has an effective thermal conductivity that ranges from 1.15 W m^{-1} K^{-1} to 1.3 W m^{-1} K^{-1} and the lower, carbonate section has an effective thermal conductivity of that ranges from about 2.7 W m^{-1} K^{-1} to 3.1 W m^{-1} K^{-1}. The corresponding gradient ranges, from Equation 1, are from 42 K km^{-1} to 57 K km^{-1} in the upper section and 17 K km^{-1} to 24 K km^{-1} in the lower section.

These conductivities characterize the rocks in their present condition, but they do not account for the effects of compaction. This point is critical to the thermal history of the Williston Basin because the clastic sections have compacted and increased in thermal conductivity by significant amounts since they were deposited. The consequences of compaction and increasing thermal conductivity tend to lower the geothermal gradient with time. Thus present temperature gradients would be lower than temperature gradients at the end of the Cretaceous assuming no increase in heat flow at present. The consequences of the change in temperature gradient with time are that temperatures in the subsurface were higher in the past than they are now and the thermal maturity of source beds is greater than would be calculated using present-day temperature data.

Table 1. Idealized profile of the Williston Basin. The thermal conductivity tables include sedimentary rock (k_r). The values for k_{pr} were determined for heat-flow logs in deep wells in the basin, and the values for k_r were calculated using Equation 4. See text for discussion of thermal conductivities.

fm/period	Age M.A.	Temp (°C)	---therm. cond. (W/m/K)--- Sed.	Water	Matrix	Thick. (km)
Present	0	5.00	1.50	0.00	1.50	>0.000
Oligocene	24	5.00	1.70	0.57	1.70	>0.000
Pierre	70	5.00	1.20	0.57	2.16	1.277
Greenhorn	88	68.86	1.20	0.66	2.03	0.101
Mowry	100	73.88	1.20	0.66	1.50	0.110
Inyan Kara	105	79.37	1.60	0.67	2.00	0.111
Jurassic	140	83.54	2.80	0.67	3.44	0.317
Spearfish	223	90.34	3.10	0.67	3.85	0.166
Minnekahta	255	93.55	2.80	0.68	3.12	0.003
Minnelusa	277	93.62	3.20	0.68	3.52	0.021
Amsden	292	94.02	3.20	0.68	3.71	0.082
Tyler	308	95.56	3.20	0.68	3.82	0.146
Charles	330	98.30	3.00	0.68	4.22	0.189
Bakken	347	109.68	1.50	0.68	1.58	0.090
Nisku	355	113.28	3.50	0.68	3.66	0.506
Interlake	410	121.96	3.50	0.69	3.60	0.392
Red River	440	128.67	3.50	0.69	3.57	0.083
Winnipeg	466	130.09	3.34	0.69	3.69	0.152
Deadwood	495	132.82	3.33	0.69	3.68	0.152
Precambrian	1700	135.56		0.69	3.50	

The change in conductivity and subsurface temperature with time can be modeled using a decompaction scheme such as that of Sclater and Christie (1980). The effects of compaction on conductivity arise from the change in porosity. We have used the Sclater and Christie (1980) model to calculate porosity and stratigraphic thickness changes. The conductivity was calculated as a function of porosity using the relation for thermal conductivity measurements on crushed rocks samples (Sass et al, 1971)

$$\text{i.e. } k_{pr} = (k_w^{f})(k_r^{1-f}) \qquad \textbf{Equation 4}$$

where k_{pr}=conductivity of the porous rock, k_w=conductivity of water, k_r=conductivity of the rock matrix, and f=porosity in per cent.

This approximation for the variation in conductivity as a function of porosity matches the general form of the empirical relations given by Sclater and Christie (1980). The change in thermal conductivity of the rock as a function of temperature is documented for a number of different rock types (Roy et al. 1982), The data show a relatively broad range of changes, and it would be most accurate to determine the response of each rock type individually. We have assumed that the change in rock conductivity is about 10 per cent for a 100 degree C change (see Roy et al, 1982) and have adjusted the rock matrix conductivity accordingly. Water increases in thermal conductivity with temperature, and we have used the data of Clark (1966) to establish a third-order polynomial to predict the change in conductivity. Conductivity values for a typical section of the Williston Basin are given in Table 1.

HEAT FLOW

Several workers previously reported heat-flow observations of about 80 to 90 mW m^{-2} in North Dakota (Combs and Simmons, 1973; Scattolini, 1977) and of greater than 100 mW m^{-2} in Saskatchewan (Marjorowicz et al, 1986). However, the high heat-flow values in North Dakota and Saskatchewan were made using an assumed thermal conductivity for the Pierre Shale of 1.7 W m^{-1} K^{-1} which is too high by about 40 to 50 per cent (Blackwell and Steele, 1981). Gosnold (1987) has made additional measurements in North Dakota and South Dakota and has recalculated previous data to determine that heat flow in the Williston Basin is about 55 to 65 mW m^{-2}. The range of about 10 mW m^{-2} is relatively small and is most likely due to variations in radiogenic heat production in the crystalline basement rocks.

Variations of heat flow in time would significantly affect the thermal history of a basin by causing changes in subsurface temperatures. For example, a 10 mW m^{-2} change in heat flow in the Williston Basin would change the temperature of the Bakken Formation by more than 10 degrees C due to the thickness of the low-conductivity clastic sections. In calculating maturity indicators such as Lopatin's Time-Temperature Index (Lopatin, 1971), such changes in subsurface temperature would have large effects.

APPLICATION TO THERMAL MATURITY

The application of Lopatin's (1971) Time-Temperature Index (TTI) to thermal maturity by Waples (1980) is shown in Table 2. Webster (1984) applied this calculation to the Bakken Formation in two wells in the Williston Basin and obtained values of 130 and 265 based on a temperature gradient of about 34 K km^{-1}. We computed TTI for three wells in the Williston Basin using four different temperature profiles:

Model A - Present temperature profile as determined by Equation 2.

Model B - Historic temperature profile as determined by the decompaction model of Sclater and Christie (1980) with thermal conductivity varying with porosity and temperature but with constant heat flow.

Model C - A profile similar to Model B but with heat flow decreasing exponentially with time.

Model D - The profile resulting from a linear geothermal gradient of 34 K km^{-1}.

DISCUSSION

The results of the model calculations are given in Table 2. The effects of decompaction and the temperature-dependent variation in thermal conductivity (Models B and C) increase the TTI values significantly for each of the wells over the TTI values calculated for constant thermal conductivity and no decompaction (Model A). The effects of an exponential decrease in heat flow from high values to the present value (Model C) to approximate a basin formation model such as that of Ahern and Mrkvicka (1984) increase the TTI values somewhat. However, because the higher heat flow would have occurred early in the basin's history, the increase is not large over the TTI values for Model B.

Table 2 Time-Temperature-Index value for three wells in the Williston Basin, computed using four different temperature profiles.

BLGS NUMBER	A	B	C	D
9264	220	290	312	73
7565	110	281	300	74
7595	115	307	336	76

The differences between the TTI values calculated using a linear-temperature-gradient model (Model D) and the more sophisticated models are significant. Waples (1980) analyzed Lopatin's (1971) TTI and indicated that oil generation occurs between TTI values of 15 and 160. All of the Model D values suggest that the Bakken is still well within the oil-generation window. The same conclusion applies to Model A which uses accurate, present-day temperatures in the TTI calculation. Models B and C more accurately approximate to the thermal history of the basin, and both indicate that the Bakken is past the oil-generation window.

The time-temperature paths for Models A, B and D for NDGS 9264 (Fig. 3) are relatively similar for the early history of the basin. However, the effects of the thick blanket of low-conductivity shales move paths A and B several tens of degrees above that of D during the Tertiary. The consequence of this thick blanket is that the temperatures within the basin rose dramatically during the Tertiary. Curve D lies between curves A and B for the early history of the basin because the gradient of 34.6 K km^{-1} exceeds the present-day gradient used for curve A.

These results suggest solutions to some problems in interpretation of thermal maturity data in previous studies. In particular, the suggestion that higher heat-flow values characterized the Williston Basin in the Cretaceous (Price et al, 1984) can be dismissed. The suggestion by Naeser (1986) that several Tertiary basins had experienced a thermal event can be similarly discounted. In general, these results suggest that thermal maturity calculations based on any linear-temperature-gradient model or even present-day temperatures may be in error not only for the Williston Basin but for any non-homogeneous basin.

ACKNOWLEDGEMENTS

Data used in this study were collected during performance of tasks that were part of U.S. Dept. of Energy Contract DE-FG07-851D12606. The computer program for the decompaction model was initially developed by Doug Anderson.

REFERENCES CITED

Ahern, J. L., and S. R. Mrkvicka, 1984, A mechanical and thermal model for the evolution of the Williston Basin, Tectonics, 3, 79-102.

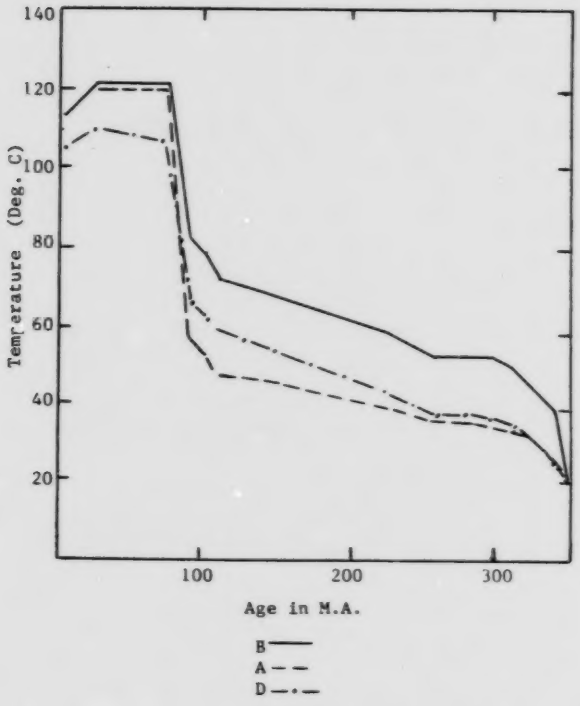


Fig. 3 Time versus temperature plots for NDGS Well Number 9264 in the Williston Basin. Curve A derives from Model A in Table 2 and is for no decompaction and constant thermal conductivity. Curve B derives from Model B and takes into account the variation in conductivity with decompaction. Curve D derives from Model D and is for a linear-temperature-gradient model.

Blackwell, D. D., and J. L. Steele, 1981, Heat flow and geothermal potential of Kansas, Final Report for Kansas Agency Contract 949, 69 pp.

Clark, S. P., Jr., 1966, Thermal conductivity. In: Handbook of Physical Constants, Clark., S. P., Jr. (ed.), Geol. Soc. Amer. Memoir 97, p. 459-482.

Combs, J. and G. Simmons, 1973, Terrestrial heat flow determinations in the north central United States, J. Geophys. Res., 78, 441-461.

Garner, D. L., and D. L. Turcotte, 1984, The thermal and mechanical evolution of the Anadarko Basin, Tectonophysics, 107, 1-24.

Gosnold, W. D., Jr., 1985, Heat flow and groundwater flow in the Great Plains of the United States, J. Geodynamics, 4, 247-264.

Gosnold, W. D., Jr., 1987, Heat flow in the Great Plains of the United States, J. Geophysical Res., (in press).

Haxby, W. F., D. L. Turcotte, and J. M. Bird, 1976, Thermal and mechanical evolution of the Michigan Basin, Tectonophysics, 36, 57-75.

Lopatin, N. V., 1971, Temperature and time as geologic factors in coalification: Akademiia Nauk SSSR, Izvestiia Seriia Geologicheskalu, 3, 95-106.

Marjorowicz, J. A., F. W. Jones, and A. M. Jessop, 1986, Geothermics of the Williston Basin in Canada in relation to hydrodynamics and hydrocarbon occurrences, Geophysics, 51, 767-779.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins, Earth Planet. Sci. Lett., 40, 25-32.

Meissner, F. F., 1978, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana. In: Williston Basin Symposium: Billings, Montana Geol. Soc., p. 207-227.

Nixon, R. P., 1973, Oil source beds in Cretaceous Mowry Shale of northwestern interior United States: Amer. Assoc. Petrol. Geol. Bull., 57, 136-161.

Nunn, J. A., N. H. Sleep, and E. W. Moore, 1984, Thermal subsidence and generation of hydrocarbons in the Michigan Basin, Amer. Assoc. Petrol. Geol. Bull., 68, 296-315.

Price, L.C., T. Ging, T. Daws, A. Love, M. Pawlewicz, and D. Anders, 1984, Organic metamorphism in the Mississippian Devonian Bakken Shale, North Dakota portion of the Williston Basin. In: Hydrocarbon Source Rocks of the Rocky Mountain Region, Woodward, J., F. F. Meissner, and J. L. Clayton (eds.), R. M. A. G., p. 83-134.

Roy, R. F., A. E. Beck, and Y.S. Touloukian, 1981, Thermophysical properties of rocks. In: Physical Properties of Rocks and Minerals, Touloukian, Y. W., W. R. Judd, and R. F. Roy (eds.), p. 409-502.

Sass, J. A., A. H. Lachenbruch, and R. J. Munroe, Thermal conductivity of rocks from measurements on fragments and its application to heat-flow determinations, J. Geophys. Res., 76, 3391-3401.

Sass, J.A., and S. P. Galanis, Jr., 1983, Temperatures, thermal conductivity, and heat flow from a well in Pierre Shale near Hayes, South Dakota, U.S. Geol. Surv. Open File Report 83-25.

Scattolini, R., 1978, Heat flow and heat production studies in North Dakota, Ph. D. thesis, University of North Dakota, Grand Forks.

Schmoker, J. W., and T. C. Hester, 1983, Organic carbon in the Bakken Formation, United States portion of the Williston Basin, Amer. Assoc. Petrol. Geol. Bull, 67, 2165-2174.

Sclater, J. G., and P. A. F. Christie, 1980, Continental stretching: An explanatin of the post-Mid-Cretaceous subsidence of the central North Sea Basin, J. Geophys. Res., 85, 3711-3739.

Turcotte, D. L., and J. L. Ahern, 1977, On the thermal subsidence history of sedimentary basins, J. Geophys. Res., 82, 3762-3766.

Waples, D. W., 1980, Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration: Amer. Assoc. Petrol. Geol. Bull., 64, 916-926.

Webster, R. L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota: In: Hydrocarbon Source Rocks of the Rocky Mountain Region, Woodward, J., F. F. Meissner, and J. L. Clayton (eds.), R. M. A. G., p. 57-82.

EARLIEST PALEOZOIC HISTORY OF THE WILLISTON BASIN IN NORTH DAKOTA

RICHARD D. LEFEVER, STEPHEN C. THOMPSON AND DOUGLAS B. ANDERSON

Department of Geology
University of North Dakota
Grand Forks ND 58202

ABSTRACT

The Deadwood Formation in the North Dakota portion of the Williston Basin ranges in thickness from zero to more than 270 m (900 ft), and represents the earliest recorded Paleozoic deposition in the North Dakota part of the Williston Basin. Six correlatable lithostratigraphic units, here informally described as members of the Deadwood Formation, can be recognized. The Deadwood Formation consists largely of siliciclastic rocks, principally quartz arenites, quartz wackes, and siltstones, and lesser amounts of carbonate rocks, with textures from mudstones to grainstones, and was deposited under marginal marine to offshore conditions.

The Winnipeg Group unconformably overlies the Deadwood Formation over most of North Dakota, and attains a maximum thickness of about 135 m (440 ft) in the center of the basin. The Winnipeg Group consists of three formations, in ascending order, the Black Island, Icebox, and Roughlock Formations. The Black Island Formation is composed of sandstones with subordinate amounts of shale, and represents fluvial/deltaic deposition in the lower part, which occurs only in western North Dakota, and shallow marine deposition in the upper part. The Icebox Formation is largely shale, with some local sandstone lithosomes, and was deposited in a deeper marine environment than was the Black Island. The Roughlock consists of argillaceous, fossiliferous limestone, and was also deposited in a deeper marine environment. The three formations are, in part, lateral facies equivalents.

The initial subsidence of the Williston Basin in North Dakota occured at a time no later than during deposition of member D of the Deadwood Formation (late Tremadocian), and perhaps even earlier, and does not appear to have been associated with major orogenic events elsewhere in North America. The area of greatest subsidence seems to have been initially elongate, and to have become more circular by Winnipeg time.

The Deadwood Formation was deposited during a gradual major eustatic sea level rise, which included several smaller-scale transgressive-regressive episodes. At the end of the Early Ordovician (latest Llanvirnian), there was a major eustatic sea level drop. Marine deposition in North Dakota ceased, and Deadwood strata were eroded from the newly exposed areas of the basin. By Late Ordovician time (early Caradocian), sea level was rising again. In North Dakota, the first evidence is the fluvial-deltaic deposits of the lower Black Island Formation, which were deposited in the area where the greatest amount of subsidence had taken place. With continued sea level rise, the deltaic deposits were covered, and the shallow marine sandstones of the upper Black Island were deposited, followed by the deeper marine shales of the Icebox Formation and, finally, by the argillaceous limestones of the Roughlock Formation.

INTRODUCTION

The stratigraphic interval encompassing the Deadwood Formation and the Winnipeg Group comprises the only record of the time span during which the Williston Basin began to subside. Thus, any discussion of the early history of the North Dakota part of the basin must rely on data from that interval. Our purpose in this paper is to describe the tectonic and depositional history of the basin during the time represented by deposition of those units, and to discuss the bearing of our findings on various ideas about the timing and early history of basin formation.

Rocks of the Deadwood Formation represent the earliest recorded Paleozoic deposition within the North Dakota portion of the Williston Basin. The Deadwood consists largely of siliciclastic rocks, with lesser amounts of fine-grained carbonates. The Deadwood Formation in North Dakota ranges in thickness from zero at its erosional edge in the eastern part of the state to more than 270 m (900 ft) in McKenzie County.

The Winnipeg Group represents the initial deposits in the Williston Basin of a Middle Ordovician transgression over most of the North American craton. The Winnipeg Group unconformably overlies the Deadwood Formation over most of North Dakota, except in the extreme eastern part of the state, where it rests directly on the Precambrian basement, and conformably underlies the Red River Formation. It attains a maximum thickness of about 135 m (440 ft) in the center of the basin. The Winnipeg consists of three formations, in ascending order the Black Island, Icebox, and Roughlock Formations.

The stratigraphy, sedimentology, and paleontology of both of these units have been studied extensively, both in outcrop (Darton and Paige, 1925; Furnish et al, 1936; Lochman and Duncan, 1950; McCoy, 1952; Kupsch, 1953; Genik, 1954; Butler et al, 1955; Kulik, 1965; Ladle, 1972; Stanley, 1984) and in the subsurface (Macauley, 1955; Ross, 1957, 1976; Andrichuk, 1959; Lochman, 1964a, 1964b, 1966; McCoy, 1958a, 1985b; Parks and Ambler, 1956; Porter and Fuller, 1958; Carlson, 1958, 1960, 1964; McLean, 1960; Fyson, 1961; Fuller,1961; Fuller and Porter, 1962; Lochman-Balk and Wilson, 1967; Paterson, 1971; McCabe, 1978; Steece, 1978; Thompson, 1984).

METHODS

The stratigraphic data for this study were derived from the interpretation of 303 logs from North Dakota wells (Fig. 1a). Subsurface control was extended a short distance outside North Dakota by the use of 60 well logs from South Dakota, Montana, Manitoba and Saskatchewan.

Depositional environment interpretations are based upon the study of approximately 600 m (2000 ft) of core from the Deadwood and Winnipeg (Fig. 1b, Table 1).

The interpretation of the early subsidence history of the Williston Basin is based in part on the use of backstripping techniques. These techniques, described in detail by Sclater and Christie (1980), estimate the amount of subsidence due solely to tectonic processes.

Table 1 - Location of wells from which cores were used.

T-R-S	NDGS Well No.	Well Name	County	Interval	Core Footage
134-87-16	8549	Shell Oil Co. Hirning-State No. 44-16	Grant	Deadwood	8905-8929
136-75-15	7146	Chevron U.S.A., Inc. Naaden No. 1	Emmons	Winnipeg	5260-5307
137-88-5	7020	Texas Pacific Steckler No. 1	Grant	Winnipeg Deadwood	10,280-10,316 10,316-10,343
138-92-21	8169	Gulf Oil Co. Leviathan 1-21-18	Stark	Winnipeg Deadwood	11,336-11,369 11,369-11,385
139-76-9	6264	Tom F. Marsh Funston No. 1	Burleigh	Winnipeg Deadwood	6080-6092 6092-6167
139-100-9	291	Amerada Petroleum Corp. Herman May Unit No. 1	Billings	Deadwood	12,993-13,225
139-101-10	3268	Amerada Petroleum Corp. Scoria Unit No. 8	Billings	Winnipeg Deadwood Deadwood Deadwood	12,605-12,631 12,631-12,652 12,677-12,876 13,363-13,381
140-65-21	370	Herman Hanson Oil Synd. Reg Ogilvie	Stutsman	Winnipeg Deadwood	3190-3208 3208-3290
141-93-28	8088	Mobil Oil Corp. William Bernhardt No. 1	Stark	Winnipeg Deadwood	12,386-12,392 12,395-12,443
141-96-2	6148	Amoco Oil Co. Heiser No. 1	Dunn	Winnipeg Deadwood	13,408-13,453 13,453-13,459
144-98-3	6228	Gulf Oil Co. Zabolotny No. 1-3-4-A	Billings	Winnipeg Deadwood	14,295-14,345 14,378-14,402
146-73-27	207	Continental Oil Co. Lueth No. 1	Wells	Winnipeg	5750-5818
150-86-15	7577	Shell Oil Co. Dewing No. 12-15	Renville	Winnipeg	9875-9934
152-95-1	2373	Amerada Petroleum Corp. Antelope Unit "A" No. 1	McKenzie	Winnipeg Winnipeg Deadwood Deadwood	14,057-14,125 14,146-14,209 14,253-14,356 15,115-15,117
152-95-6	8090	Amerada Hess Corp. Grimistad No. 4-6	McKenzie	Winnipeg Deadwood	14,615-14,617 14,617-14,643
156-95-16	1385	Amerada Petroleum Corp. N.D. "A" No. 9	Williams	Winnipeg	14,129-14,170
158-62-29	20	Union Oil Co. Aanstad No. 1	Ramsey	Winnipeg	3059-3112
161-85-1	6624	Shell Oil Co. Osterberg No. 22X-1	Renville	Deadwood	9155-9308
163-87-10	6401	Shell Oil Co. Wisdahl No. 23-10	Renville	Winnipeg Deadwood	9244-9292 9292-9453
163-95-18	7087	Shell Oil Co. Svangstu No. 24-18	Divide	Deadwood	11,637-11,669
163-102-7	2010	Carter Oil Co. Moore No. 1	Divide	Winnipeg	10,863-10,940

Fig. 1 A) Locations of wells in North Dakota from which well logs were examined. B) Locations of wells in North Dakota from which cores were examined.

STRATIGRAPHY

DEADWOOD FORMATION

Numerous authors have proposed informal divisions for the Deadwood Formation at the type section in the Black Hills (Butler et al, 1955; Kulik, 1965; Ladle,1972). Carlson (1960) recognized the presence of three lithologic units in the Williston Basin subsurface. With the increase in the quality and quantity of geophysical well logs since Carlson's study, Thompson (1984) was able to recognize that certain beds within the Deadwood could be traced throughout the Williston Basin.

Six correlatable lithologic units exist within the Deadwood Formation in the Williston Basin. They were initially chosen on the basis of well log parameters, and analysis of cores shows that each has distinctive lithologic characteristics and represents a lithostratigraphic unit. These units are here informally described as members of the Deadwood Formation, and labelled, in ascending order, A through F.

Member A

Member A is a basal quartz arenite to glauconitic quartz arenite with minor conglomerate and "granite wash." The unit corresponds to the "thin basal sandstone" identified by Carlson (1960) and to the lower member of the Deadwood type section (Kulik, 1965). Within North Dakota, the A member uncomformably overlies the Precambrian basement. The nature of the contact with the overlying B member is uncertain, but probably is unconformable. Cores of this contact from northern North Dakota show that the upper several feet of member A, which is highly glauconitic, have been oxidized to a hematitic, glauconitic quartz arenite, suggesting a period of subaerial exposure and weathering.

In the North Dakota portion of the Williston Basin the A member, where present, varies from 2 to 48 m thick (8-157 ft). Its erratic distribution appears to be controlled largely by the relief on the Precambrian basement (Kulik, 1965, noted that the distribution of the basal unit within the Black Hills was variable and controlled by deposition in schist valleys and around quartz ridges). Due to the increase in sandstone to the east in the overlying B member, the eastern limit of member A cannot be determined; A and B are thus undifferentiated in eastern North Dakota (Fig. 4b). A clean basal sandstone unit is traceable on logs north into Saskatchewan and Manitoba.

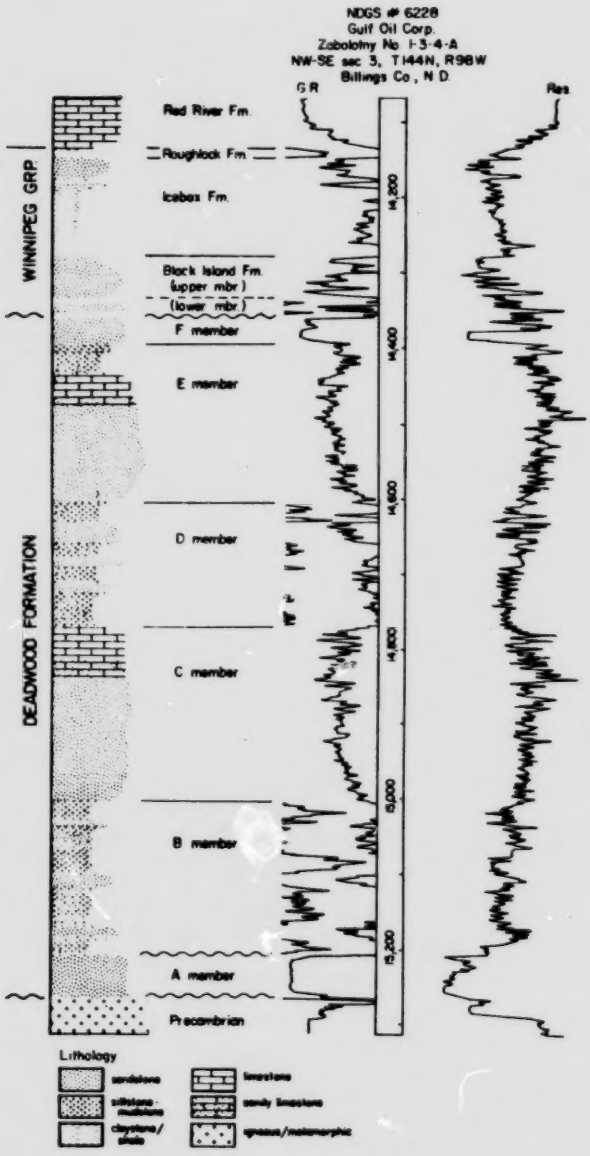


Fig. 2 Typical lithologic column and well log responses for Deadwood Formation and Winnipeg Group.

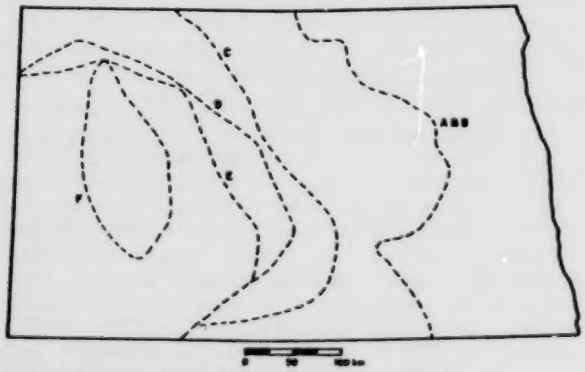


Fig. 3 Approximate areal limits of members of the Deadwood Formation.

Three different lithologies occur in cores of this member. Locally, a poorly sorted basal conglomerate overlies the basement; it contains metamorphic pebbles, quartz, feldspar, and up to 25% glauconite, and is interbedded with thin layers of very fine laminated sand. No sedimentary structures are evident.

A second lithology consists of a very fine- to coarse-grained, well sorted quartz arenite, with minor amounts of interbedded thin shales. Where this sandstone lies on the Precambrian, minor amounts of granule-sized quartz grains occur. Although most of this lithology is massive, some minor cross-bedding is present in the basal sandstone at one locality (NDGS 2373). The only fossils present are unidentifiable fragments.

The third lithology consists of a highly glauconitic, very fine to very coarse, faintly cross-bedded quartz arenite, with occasional thin clay laminae with burrow structures and minor soft sediment deformation.

Member B

Member B consists of glauconitic to quartzose siltstone, very fine sandstone, and minor claystone. To the east and the south this unit shows an increase in the amount of sandstone, making differentiation from the underlying A member difficult. In North Dakota, member B may unconformably overlie either the A member or the Precambrian basement. It is overlain with a comformable, partly gradational contact by member C in western North Dakota or unconformably by the Winnipeg Group in eastern North Dakota. Where it occurs within North Dakota, the B member ranges from 8 to 110 m in thickness (26 - 360 ft). Its thickness is also controlled partially by Precambrian paleotopography. This member thickens west into McCone County, Montana, due to the development of a sandstone unit. Correlation of wells within Divide County shows a significant loss of section within the unit, indicating an intraformational unconformity in that area.

The dominant lithology of this member is a quartzose siltstone with a glauconite content ranging from 5% to 60%. The glauconitic siltstone locally contains hematitic layers, suggesting the possibility of oxidation during subaerial exposure. Unidentifiable fine sand-sized fossil debris occurs sporadically throughout the siltstone. Sedimentary structures include horizontal parallel lamination, ripple cross-lamination, and soft-sediment deformation. Many of the siltstones contain thin wispy clay laminae and clay matrix, and grade into mudstones. Claystone layers in core range up to about 2 m thick (6 ft) and tend to have well-developed fissility. The claystone is noncalcareous, and contains local unidentifiable fossil debris.

Sandstones in the western portion of the state constitute a subordinate lithology. They vary from glauconitic quartz arenites to wackes, contain a lower percentage of glauconite than the siltstones, and are coarse silt- to very coarse sand-sized. These sandstones show horizontal parallel laminations and soft sediment deformation structures. No vertical trend in the various lithologies is evident. To the east, sandstones become dominant in this member, and are very fine- to fine-grained, well-sorted glauconitic quartz arenites to glauconite arenites. Glauconite constitutes from 5% to 60% of the sandstones.

Member C

Member C consists predominantly of very fine- to medium-grained sandstone with lesser amounts of mudstone and carbonate. In the western part of the state member C consists,

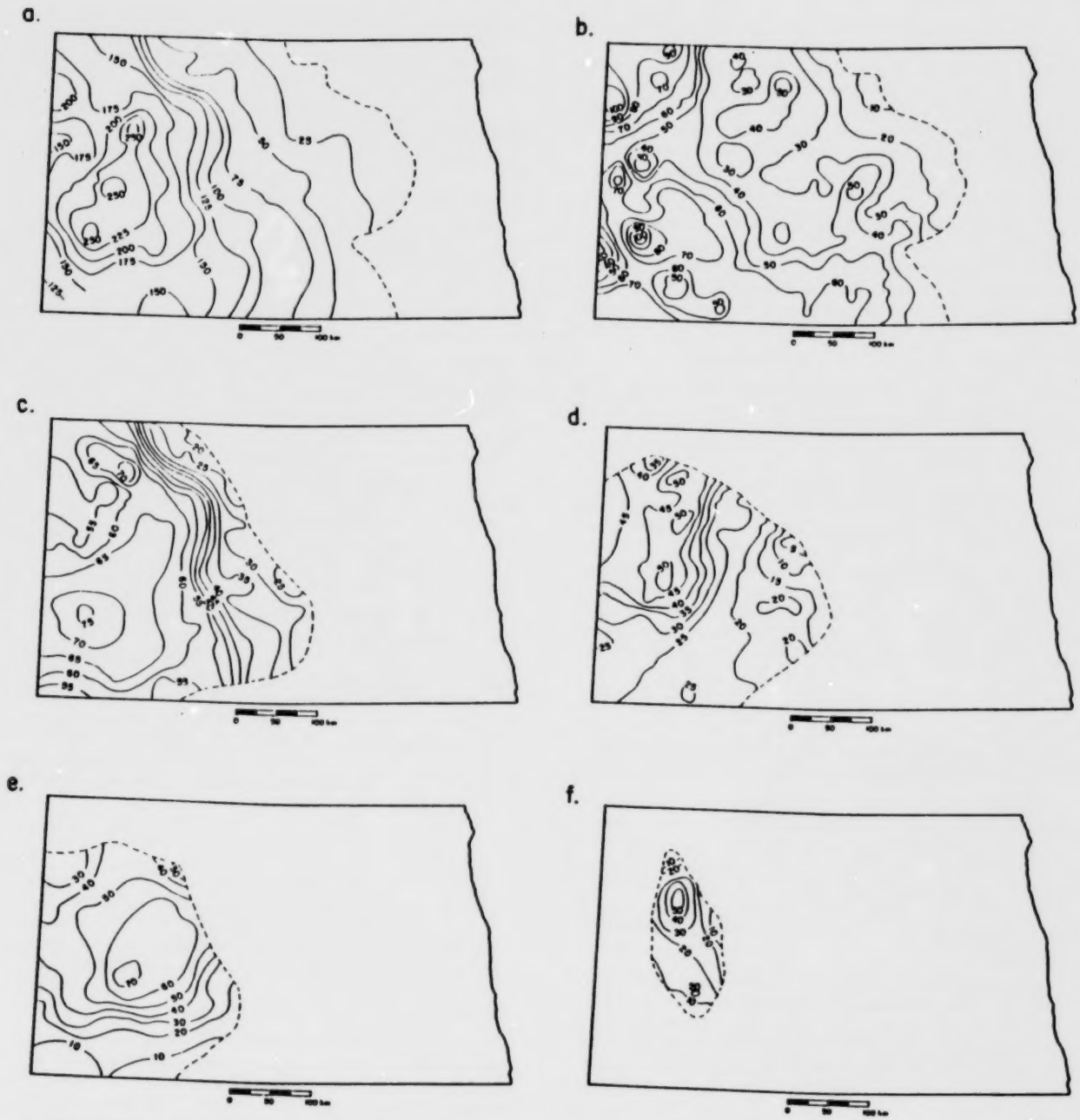


Fig. 4 Isopach maps of the Deadwood Formation (dashed lines represent erosional limits of the formation and members). a) Isopach map of the Deadwood Formation (contour interval = 25 m); b) Isopach map of members A and B (contour interval = 10 m); c) Isopach map of member C (contour interval = 5 m); d) Isopach map of member D (contour interval = 5 m); e) Isopach map of member E (contour interval = 10 m); f) Isopach map of member F (contour interval = 10 m).

in ascending order, of sandstone, an interbedded sandstone-limestone unit, and an upper carbonate mudstone to grainstone. Eastward, the lower sand becomes increasingly porous and clean, and thickens at the expense of the mixed sandstone-carbonate unit, and the upper carbonate is replaced by interlaminated anhydritic dolomite and siltstone, and ultimately by a clean porous sandstone. In southern North Dakota and South Dakota the entire C member consists of porous sandstone. The lower part of member C is correlative with the "*Scolithos* sandstone" of the upper portion of the Deadwood in the Black Hills. The C member conformably overlies the B member except for one well in Morton County where it overlies the Precambrian basement. Member C is conformably overlain by the D member or unconformably overlain by the Winnipeg Group. Where the anhydritic dolomites and siltstones occur at the top of member C, the contact with member D is gradational. Within North Dakota the C member varies from 11 to 80 m thick (37 to 261 ft), and is the lowest unit whose isopach pattern is not directly controlled by the Precambrian paleotopography (Fig. 4c).

The sandstone lithology consists primarily of a very fine- to medium-grained, well sorted quartz arenite, with some fine-grained glauconite. Structures include horizontal parallel laminations and cross-bedding. Vertical *Scolithos* burrows are common in the cross-bed sets. In western North Dakota, these rocks are cemented with calcite or quartz; to the east, where the sandstones are overlain by the anhydritic dolomites and siltstones, the upper portion of the sandstone has been cemented by anhydrite or calcite and dolomite.

A second type of sandstone is a quartz wacke, which is interbedded with the arenites. The wackes generally are finer grained than the arenites (very fine- to fine- grained), poorly to moderately sorted, with thin wispy clay laminae. The wackes have a disrupted structure, resulting from bioturbation or soft sediment deformation; some remnant planar lamination is also present.

The interbedded sandstone-carbonate unit ranges from bioturbated, sandy, fossiliferous wackestone to fossiliferous quartz wacke with lesser carbonate mudstone, and intraclastic fossiliferous packstones. The siliciclastic-carbonate lithology contains subequal amounts of very fine- to fine-grained quartz sand, fossil hash, and ooids partially recrystallized to a microspar calcite. This lithology also contains thin wispy clay laminae which have been mixed with the coarser grains by soft sediment deformation or pervasive bioturbation. The intraclastic packstones contain pebbles of fossiliferous wackestones, typically with glauconitic coatings. The mudstones have few fossils, although some of them grade to fossiliferous wackestones. As a result of soft-sediment deformation, the mudstones have a nodular fabric, and may be intermixed with clastic textures.

The upper carbonate is similar to carbonates in the underlying transitional unit but lacks the high siliciclastic content. Varieties range from mudstones to trilobite-echinoderm grainstones, which are interbedded in a complex sequence.

Eastward, the upper carbonate changes to an interlaminated anhydritic dolomite and siltstone. These lithologies contain glauconite as flattened granules, rounded grains, and as a film in clay laminae. Dolomite occurs in layers as individual rhombs or interlocking anhedral crystals. Siltstone ranges from coarse silt to very fine sand, and contains quartz or dolomite cement. This unit exhibits abundant soft-sediment deformation.

In south-central North Dakota, to the east and south of the area where the dolomite and siltstone lithology predominates, the top of the C member is a clean porous sandstone indistinguishable on logs from the remainder of the C member. No cores of this lithology have been cut, but it is probably a quartz arenite similar to those that occur lower in member C.

Member D

Member D consists of interbedded siltstone, mudstone, sandstone, and minor carbonate. Where present, the D member conformably overlies the C member throughout the study area. This lower contact appears highly gradational on logs in the area of the dolomite and siltstone facies of the C member, although no cores containing both units were available. Member D is overlain with a comformable, gradational contact by member E or unconformably by the Winnipeg Group to the east and the south. Within the Williston Basin the D member ranges from 2 to 59 m thick (6 to 194 ft; Fig. 4d). Due to erosion, member D is restricted to the western half of North Dakota, eastern Montana, and extreme northern South Dakota. No correlative unit exists in the type section in the Black Hills. A local thickening occurs within member D in an area extending from central Billings County to eastern McKenzie County; the additional section appears to be due to a locally developed sandstone.

Lithologically, member D shows a vertical change upwards from wavy-bedded argillaceous, fossiliferous carbonate mudstones and shales to wavy-bedded calcareous siltstone and shale to horizontally parallel-laminated and bioturbated calcareous siltstones and sandstones.

The lower portion of the D member consists of a silty fossiliferous carbonate mudstone with wispy clay laminae, which has been disturbed by soft sediment deformation and bioturbation. The mudstone contains common sand-sized glauconite, and up to 5% fossil debris, which consists primarily of echinoderms, brachiopods and trilobites; it is locally interbedded with thin (<4 mm thick) layers of an intraclastic fossiliferous packstone. The packstone contains glauconite-coated mudstone intraclasts up to 3 cm long (1 inch), and trilobite and brachiopod debris in a micrite to microsparite matrix. The siliciclastic content of this member gradually increases upward into a calcareous siltstone-very fine sandstone with wavy-bedded clay laminae. This lithology has a mottled appearance due to bioturbation or soft sediment deformation. Discrete horizontal burrows occur along some bedding planes. Thin layers of an intraclastic fossilferous wackestone-packstone occur in this lithology and are similar to those in the underlying less silty beds.

With further upward increase in siliciclastics, the member changes to interlayered mudstones, siltstones, and sandstones. The sandstones are very fine- to fine-grained quartz arenites to wackes. The dominant structures in the sandstones are horizontal parallel laminations, occasionally with soft-sediment deformation due to water escape. Some burrows are present along bedding planes. Glauconite is a minor constituent in most of this lithology, although in one core a thin layer of glauconite arenite is present, with up to 80% very fine- to medium-grained glauconite.

Member E

Member E consists predominantly of very fine- to coarse-grained sandstone overlain by a thin sandstone-limestone unit, a wackestone-packstone interval, and a mottled sandstone-shale unit. Member E is restricted to eastern Montana and the western half of North Dakota; it ranges from 2 to 78 m thick (6 to 225 ft). The isopach of this member reflects the present structure of the Williston Basin (Fig. 4e).

This member consists of quartz arenites and quartz wackes. The arenites are well sorted, very fine- to coarse-grained, and generally become coarser upward from the silts and fine sands of the D member; silt and clay laminae are sometimes interbedded with the sandstones. Although some of the arenites are massive, sedimentary structures occur in most beds, including cross-bedding, horizontal parallel laminations, and water escape structures, and vertical infilled *Scolithos* burrows. Fossils occur in this member in only one of the cores examined (NDGS 291). The fossiliferous bed contains abundant calcareous pellets and several gastropod steinkerns.

Quartz wackes in member E appear to have resulted from mixing of arenites and interbedded clay laminae by soft sediment deformation or bioturbation. In addition to *Scolithos* burrows, horizontal traces, including *Planolites* and an unidentified zoned form, similar to forms associated with the *Cruziana* ichnofacies, occur in the wackes.

The limestone is an echinoderm-brachiopod-trilobite wackestone to packstone. A thin sandstone-limestone unit underlies this lithology, and is a sandy fossiliferous packstone.

The mottled sandstone-shale unit is a mixture of calcareous very fine sand to coarse silt with wispy clay laminae. The mottled texture is due to soft-sediment deformation; some minor remnant planar laminations are present. The sandstone and shale are interbedded with thin layers of a sandy fossiliferous peloidal wackestone to packstone to intraclastic fossiliferous packstone.

Member F

Member F is composed predominantly of very fine- to coarse-grained sandstone and minor siltstone, mudstone, and carbonate. Member F conformably overlies member E and is unconformably overlain by the Black Island Formation of the Winnipeg Group. This unit is the most areally restricted of the members of the Deadwood, and is limited to west-central North Dakota. Member F ranges from 3 to 53 m thick (10 to 173 feet); the greatest thickness is in eastern McKenzie County, near the depocenter of the Williston Basin. The isopachs reflect the concentric pattern of the basin (Fig. 4f).

The sandstones of member F consist primarily of quartz arenites and quartz wackes. The quartz arenites are very fine- to very coarse-grained and well sorted. Structures include horizontal parallel laminations, cross-bedding, and vertical *Scolithos* burrows. In the quartz wackes, primary sedimentary structures are lacking, although there is abundant evidence of bioturbation and soft-sediment deformation. Minor thin beds of siltstone and claystone are mottled, probably as a result of soft-sediment deformation. The claystones are up to 10 mm thick and are only slightly calcareous. They contain trilobite and brachiopod debris and graptolite fragments. The siltstones have a higher calcite content than the claystones; they grade into silty fossiliferous wackestones, where the fossil content ranges up to 30%.

Associated with the silty limestone is a thin (<12 cm) layer of wackestone-packstone containing about 20% unidentifiable fossil debris.

WINNIPEG GROUP

The Winnipeg Group unconformably overlies the Deadwood Formation over most of North Dakota, except in the extreme eastern part of the state, where it rests directly on the Precambrian basement. It attains a maximum thickness of about 135 m (440 ft) in the center of the basin. The Winnipeg consists of three formations, in ascending order, the Black Island, Icebox, and Roughlock Formations.

Black Island Formation

The Black Island Formation unconformably overlies the Deadwood Formation, except in eastern North Dakota, where it rests directly on Precambrian crystalline rocks. It is conformably overlain by the Icebox Formation. On the basis of well log interpretation and core description, the Black Island is here divided informally into lower and upper members, each of which is composed of two distinct lithofacies.

Lower Member of the Black Island Formation: As indicated on the isopach map (Fig. 5b), the lower member of the Black Island is located almost entirely in the western half of North Dakota. It has a maximum thickness of more than 30 m (100 ft) in the area of the Nesson Anticline.

There are two lithofacies within the lower member of the Black Island Formation: a red-bed lithofacies and a green quartz wacke lithofacies. The red-bed lithofacies consists of dark reddish brown sandstone and shale, while the green quartz wacke lithofacies is composed mostly of a light greenish gray quartz wacke.

A dark reddish brown, quartz arenite lithotype is a major constituent of the red-bed lithofacies; it is commonly fine- to medium-grained and well sorted. Although it is more commonly structureless, the quartz arenite is finely laminated in some places; no fossils were found in it, and there is no evidence of bioturbation. It is usually well indurated, but becomes friable with an increase in the content of interstitial clay.

The reddish brown quartz arenite is of variable thickness with beds ranging from about 30 cm to 6 m (1 - 20 ft) in thickness. In places, the quartz arenite is interlaminated with lesser amounts of reddish brown mudstone or white quartz arenite. The reddish brown quartz arenite may rest upon, or may underlie, either a red shale lithotype or rocks of the green quartz wacke lithofacies.

The red shales are characterized by a sequence of dark red shales and interbedded dark red and dark green shales. These shales are often finely laminated (1-3 mm) and are in places interbedded with thin lenses of fine-grained cross-bedded sandstone or mudstone. The red shales also contain mud cracks and red siltstones with horizontal laminations. As in the red quartz arenites, bioturbation is absent, and no fossils were observed. These shales are often interbedded with the red quartz arenite lithotype higher in the section of the lower member of the Black Island. The red-bed lithofacies contains both fining-upward and coarsening-upward sequences.

The other major lithofacies in the lower portion of the Black Island Formation is a green quartz wacke. This lithology is characterized by poorly sorted, fine- to coarse-grained, light greenish gray, argillaceous quartz wacke. Locally, thin lenses of light green shale alternate with the quartz wacke or with a less common well-indurated quartz arenite.

Upper Member of the Black Island Formation: The upper member of the Black Island Formation is composed primarily of sandstone. It conformably overlies the lower member of the Black Island and is conformably overlain by the shale of the Icebox Formation. As shown in the isopach map, this member is present over a large portion of North Dakota. It reaches a maximum thickness of about 50 m (165 ft) in northwestern North Dakota, in the area of the Nesson Anticline (Fig. 5b). The upper member of the Black Island thins rapidly east and south from the thickest section and thins to a feather edge along the southern border of North Dakota. In much of eastern North Dakota, the upper member of the Black Island is absent or, where present, is only up to about 5 m (15 ft) thick. Two lithofacies occur within the upper member of the Black Island Formation: a quartz arenite lithofacies, and a green quartz wacke lithofacies.

The quartz arenite lithofacies is dominated by a well-sorted, fine- to medium-grained, quartz-cemented structureless quartz arenite. A subordinate rock type in this lithofacies is a fine- to medium-grained, bioturbated quartz wacke. The structureless quartz arenites are irregularly interbedded with the bioturbated quartz wackes, and vertical changes between the two lithotypes are usually gradational.

The other lithofacies in the upper member of the Black Island contains just one lithotype, a green quartz wacke. The quartz wacke is a friable to moderately indurated, fine- to medium-grained, quartz wacke. This rock type is quite similar to the green quartz wacke of the lower member of the Black

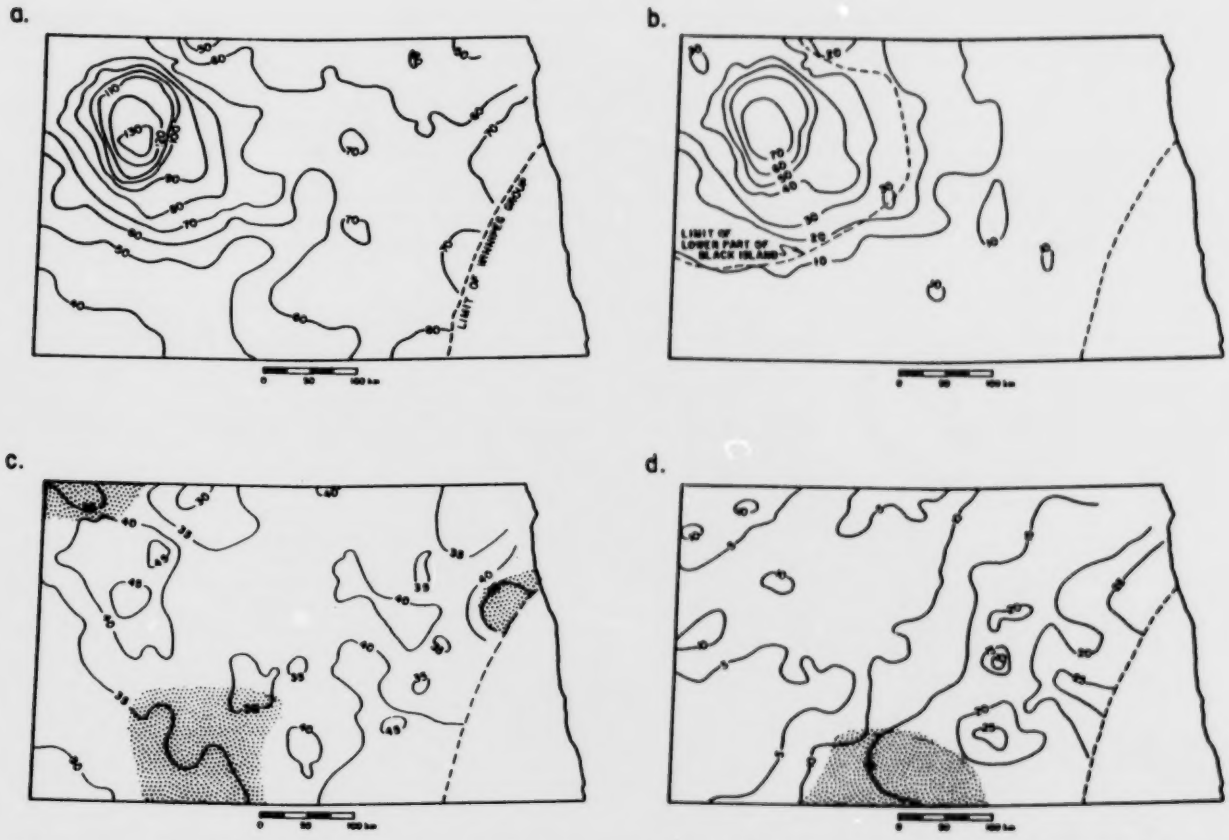


Fig. 5 Isopach maps of Winnipeg Group strata (dashed lines represent erosional limits of group). a) Isopach map of Winnipeg Group (contour interval = 10 m); b) Isopach map of Black Island Formation (contour interval = 10 m). Dotted line represents areal limits of lower member of Black Island Formation; c) Isopach map of Icebox Formation (contour interval = 5 m). Stippled areas indicate the extent of the sandstone lithosomes discused in the text; d) Isopach map of Roughlock Formation (contour interval = 5 m). Stippled area indicates the extent of the sandstone lithosome discussed in the text.

Island. The lithotype is both underlain and overlain by the quartz arenites, usually with a gradational lower contact and a sharp upper contact.

Icebox Formation

The Icebox Formation is composed primarily of shale. It has comformable, gradational contacts with both the sandstones of the underlying Black Island Formation and with the overlying argillaceous limestones of the Roughlock Formation. Except for extreme eastern North Dakota, where post-Red River erosion has removed Winnipeg strata, the Icebox is present over the whole state. As shown by the isopach map, the Icebox is nearly 50 m (165 ft) thick in Grand Forks County and more than 45 m (150 ft) thick in the central basin area of northwestern North Dakota (Fig. 5c).

Much of the shale of the Icebox Formation is bioturbated, and, in some places, contains distinct worm burrows. Some of these shales are fossilferous and contain brachiopods, trilobite fragments, and other, unidentified, fossil fragments. The Icebox shales locally contain black phosphate nodules, as well as slickensides.

Sandstone is present in the Icebox Formation in two sandstone bodies that have been cored, one in Divide County, and the other in Grand Forks county, and a third uncored body in southwestern North Dakota. The first two of these lithosomes, at least, are characterized by fine- to medium-grained quartz wacke. The sandstone body in Divide County is highly bioturbated and argillaceous and, in places, cross-laminated. The contact between the Divide County sandstone and the overlying shale is gradational; the upper 3 m (10 ft) of this sandstone becomes increasingly argillaceous as it grades upward into siltstone, and finally into shale. The sandstone in Divide County attains a maximum thickness of about 14 m (45 ft). The quartz wacke in Grand Forks County is also gradational with the enclosing shales of the Icebox Formation, and is up to 18 m (60 ft) thick. The sandstone body in southwestern North Dakota (as yet uncored) underlies large portions of Grant, Morton, Adams, Hettinger, and Stark Counties. This body is up to 9 m (30 ft) thick, and well log responses indicate that the sandstone is interbedded with thin layers of shale.

Roughlock Formation

The Roughlock Formation is transitional between the noncalcareous shale of the underlying Icebox Formation and the limestone of the overlying Red River Formation and has characteristics of both.

The dominant lithology of the Roughlock Formation is a limestone, which is predominantly a nodular microsparite in a matrix of argillaceous, dolomitic fossiliferous wackestone. Fossils within this lithotype include fragments of brachiopods, trilobites, echinoderms, as well as some unidentified fossils. Well log responses indicate that the Roughlock is relatively homogenous in lithology throughout the state. A notable exception to this homogeneity is a sandstone lithosome, up to

12 m (40 ft) thick, in south-central North Dakota. Although this interval has not yet been cored, well log responses indicate that it is composed of sandstone interbedded with thin shales.

The Roughlock Formation is 27 m (90 ft) thick just west of the area where it is erosionally truncated, near the eastern border of the state. The Roughlock gradually thins to the west and averages about 5-10 m (20-30 ft) thick over the western third of the state, and is very thin near the northwest corner of the state (Fig. 5d).

Near the contact with the underlying Icebox Formation, the Roughlock consists of interbedded argillaceous limestone and calcareous shale; in most locations the contact appears to be gradational. The contact with the overlying Red River Formation also appears to be gradational, as the limestones of the Roughlock become gradually less argillaceous upward into the clean Red River carbonates.

INTERPRETATION

DEPOSITIONAL ENVIRONMENTS

Deadwood Formation

The six members of the Deadwood are composed of nine lithologies: 1) Quartz arenite and conglomerate (basal member A); 2) Glauconitic quartzose siltstone, sandstone, and glauconite arenite (member B); 3) Mottled to wavy-bedded silty biomicrite to calcareous siltstone (lower member D, upper E, and minor beds of lower F); 4) Parallel-laminated sandstone and siltstone (member D and minor beds of lower F); 5) Massive to parallel-laminated to cross-bedded quartz arenites and mottled quartz wackes (lowest member C, lower E, and F); 6) Interbedded sandstone-limestone (middle C and middle E members); 7) Carbonate mudstone to packstones and grainstones (upper C member and E); 8) Intraclastic wackestones and packstones (thin beds in members C, D, and E); and 9) Anhydritic dolomites and siltstones (upper C member).

Interpretation of the basal member is limited due to lack of an adequate vertical section in core. A number of environments have been proposed for comparable Cambrian basal clastic units including beach or barrier island (Deadwood Formation of South Dakota, Stanley, 1984), braided fluvial, marine foreshore to shoreface, and tidal flat and channel deposits (Mt. Simon Formation of Wisconsin, Driese et al, 1981), and braided fluvial to shallow marine transition (Bradore Formation of Labrador, Hiscott et al, 1984).

The proximity to Precambrian paleotopography which was exposed to weathering during the Early and Middle Cambrian suggests that much of the conglomeratic material could be attributed to alluvial deposition. Where cored, the conglomerates contain glauconite in the matrix, which suggests a shallow marine origin or reworking of these conglomerates. The clean, well sorted, mature, massive to cross-bedded quartz arenites, containing a trace of fossil material, suggest an upper shoreface to foreshore marine setting. The inclusion of glauconite in some arenites indicates a proximity to an opep marine quiet-water environment, perhaps with shoreward transport of the glauconite.

Member B is so glauconite-rich that it might be considered a "glauconite facies." In the Black Hills, Stanley (1984) attributed the correlative interval, which is dominated by shale and limestone pebble conglomerates and interbedded glauconitic sandstone, siltstone, and minor shale, to low-energy subtidal lagoon and tidal sand flat deposition. The abundant glauconite and fine clastics in this member are indicators of a quiet, nonturbulent environment with slow deposition, below mean low tide and fair-weather wave base. In this interval, there is no indication of intermittent exposure, such as desiccation cracks or rip-up clasts; a tidal flat environment therefore seems less likely than a deeper marine one. The eastern increase in the grain size indicates the direction of the strand line, but the lack of cores in this area makes it impossible to determine whether wave or tidal processes were dominant.

The siliciclastics and carbonates of the Lower Ordovician members upper B through F form vertical sequences representing a shelf transition from a distal carbonate buildup to a marginal marine setting. Each sequence, from base to top, consists of: 1) sandy limestones; 2) carbonate mudstones to grainstones; 3) silty fossiliferous carbonate mudstones, grading upwards to calcareous mottled and wavy bedded siltstones, parallel-laminated siltstones and very fine sandstones; and 4) cross-bedded to parallel-laminated quartz arenites and mottled to bioturbated quartz wackes.

The lower carbonate mudstone-grainstone lithologies were separated from the coastal siliciclastics by a broad shallow shelf. The extremes of the limestone textures range from grainstone, formed on shallow high-energy buildups, to mudstones desposited in lower energy conditions or trapped by organisms on the buildups. Shoreward, the amount of silt and clay increased, hindering carbonate production; the silty fossiliferous mudstone to calcareous siltstone was probably deposited in a quieter, more offshore position. Within these lithologies are thin laminae of intraclastic wackestones and packstones, which are probably the result of occasional storms producing rip-up clasts, and carrying fauna onto the deeper shelf from the carbonate buildup. Intraclasts with a glauconitic coating similar to those on these clasts have been reported from the Cambrian of Montana and Wyoming, where they are associated with subtidal lagoonal facies (Sepkoski, 1982; Brett el al , 1983). Formation of the glauconite coating required exposure during slow deposition in a subtidal setting subsequent to storm events.

Shoreward, these wavy-bedded siltstones change to the parallel-laminated siltstones and sandstones of the lower shoreface. The cross-bedded quartz arenites are representative of the upper shoreface and possibly foreshore position. Bioturbation in the higher-energy cross-bedded arenites is limited to the *Scolithos* ichnofacies, a condition which led Stanley (1984, p. 189-190) to attribute sandstones such as the "*Scolithos* sandstone" of the Black Hills to beach or barrier island deposition. The quartz wackes contain clay laminae and are more heavily bioturbated, indicating deposition during periods of lower energy or in protected areas of coastal ponds or the backshore areas, as were the thin beds of calcareous mottled siltstones.

The sandstone-carbonate transitional lithology was produced in a high-energy environment at the distal setting, where sand was eroded from the shelf floor and mixed with coarser carbonate grains.

The anhydritic dolomite and siltstone probably represent deposition in a protected lagoonal setting, based on the occurrence of dolomite. Intermittent exposure may have caused precipitation of anhydrite and desiccation.

Winnipeg Group

Black Island Formation: The reddish brown color is the most obvious characteristic of the lower member of the Black Island Formation; both the quartz arenite and shale, the dominant lithotypes of the red-bed lithofacies, are predominantly a dark

reddish brown color. Red sediments are usually indicators of continental environments, although other environments can also produce this color.

The structureless nature of the shale, which comprises much of the red-bed lithofacies, suggests rapid deposition from suspension. Parallel, horizontal stratification, such as in the horizontally laminated siltstones, represents episodic sedimentation in still water. Mudstones interbedded with sandstones indicate intermittent slack water periods when clay settled out between periods of traction transport of sand and silt. Cross-stratification, such as that of the fine-grained sandstones, records relatively high-energy, turbulent flow conditions. The occurrence of thin, cross-stratified sandstone layers within the shale unit suggests widely fluctuating current conditions. Mudcracks are usually caused by desiccation of clay under subaerial conditions. All of the characteristics described above are suggestive of a terrestrial, probably fluvially-dominated setting, such as a floodplain or delta plain. The thick deposits of reddish brown quartz arenite of the red-bed lithofacies may represent channel deposits. On the basis of the textural and structural characteristics, and the lithologic successions, we tentatively assign a fluvial, probably a delta plain, origin to the red-bed lithofacies of the lower member of the Black Island. Several criteria which tend to characterize deltaic plain depositional environments (Turner, 1980, p. 67), include sandstone channel and bank deposits of a red or drab color, mudstone floodplain deposits of red or variegated colors, and fining- and coarsening-upward sequences, and are met within the rocks of this lithofacies.

It is not certain in what environment the green quartz wacke lithofacies of the lower member of the Black Island Formation was deposited. These rocks may have formed as a result of the weathering of pre-existing strata of the lower member of the Black Island Formation. However, a more likely explanation for the origin of this lithofacies is that these rocks were the initial deposits of the transgression that later deposited the quartz arenite of the upper member of the Black Island. Rock associations tend to support the second of these hypotheses. The occurrence of the green quartz wacke lithofacies in both the lower and upper members of the Black Island may be evidence of intertonguing between the two members. The presence of intertonguing is important because it suggests that a facies relationship exists between at least a portion of the lower and upper members of the Black Island.

The upper member of the Black Island Formation is interpreted to have been deposited in a nearshore environment, in the zone that lies between those areas dominated by beach processes and those dominated by marine shelf processes; water depths range from about 10-30 m (30-100 ft), the dominant processes are wave processes (both normal and storm-driven).

The upper member of the Black Island Formation is dominated by the rocks of the quartz arenite lithofacies. The parallel laminations of the quartz arenite lithotype may represent upper flow regime conditions with deposition from suspension. The laminations may also represent hummocky cross-stratification. Hummocky cross-stratification is characterized by gently undulating bed boundaries with laminae almost parallel to the lower bound surface (Reineck and Singh, 1980, p. 100), and occurs in the lower part of shoreline sequences, especially under high wave conditions. However, the large scale and the roughly horizontal orientation of the laminae make hummocky cross-stratification difficult to recognize in cores. The paucity of fossils within the quartz arenite lithofacies supports an interpretation of a nearshore environment in that the high energy of nearshore conditions increases the mobility of the substrate, making conditions less favorable for the survival of benthos.

A nearshore interpretation for the quartz arenite lithofacies is also supported by the nature of the adjacent rock units. The upper member of the Black Island Formation is conformably underlain by what are interpreted to be the continental deltaic plain deposits of the lower member of the Black Island and conformably overlain by shales of the Icebox Formation (which are probably of offshore origin). The position of the upper member of the Black Island between continental deposits and a thick shale section makes a nearshore environment interpretation for that unit reasonable.

The rocks of the green quartz wacke lithofacies of both the lower and upper members of the Black Island are lithologically very similar. It is not likely that weathering of rocks as different as those of the red-bed lithofacies and the quartz arenite lithofacies would result in the same lithology. It is more plausible that the green quartz wacke lithotype of the two members is similar as a result of similar depositional conditions. The occurrence of the green quartz wacke lithofacies interbedded with lithofacies of both the lower and upper members suggests that the green quartz wacke may be transitional between the other lithofacies in the lower and upper members and may represent the basal deposits of the Middle Ordovician transgression, perhaps as beach or other marginal marine deposits. If these deposits are indeed of the same origin, the intertonguing supports the interpretation that a facies relationship exists between the lower and upper Black Island.

Icebox Formation: The Icebox Formation is interpreted to have been deposited in an offshore environment, adjacent to and seaward from a nearshore environment. Marine invertebrates, such as the orthid and strophomenid brachiopods, clearly identify the Icebox as marine in origin, and probably indicate relatively open conditions with normal salinities. The presence of epifaunal suspension feeders (brachiopods) and abundant horizontal burrows suggest that the upper portion of the substrate contained mild oxidizing conditions.

The lower part of the Icebox Formation was probably deposited in deeper water than, or at least some distance seaward from, the nearshore sand deposits of the upper member of the Black Island.

The three sandstone lithosomes of the Icebox Formation probably represent three distinct environments of deposition. The sandstone lithosome in northwestern North Dakota (Divide County) probably represents a nearshore deposit similar to that of the quartz arenite lithofacies of the upper member of the Black Island. The lower part of this lithosome has not been cored, but the cross-laminated sandstone present in the middle of this lithosome, suggesting deposition under lower flow regime conditions, is overlain by horizontally laminated and bioturbated sandstones which become increasingly shaly upward until they grade into a typical Icebox shale section. Log responses indicate that the lower contact of the Divide County lithosome is also gradational from the underlying shale. This sandstone lithosome might be a tongue of the upper member of the Black Island; more data may show the upper member of the Black Island and the sandstone lithosome of the Icebox in Divide County to be physically continuous. The depositional sequence in the Icebox in Divide County suggests that a transgression (marked by the transition from sandstones of the Black Island to the shales of the Icebox) was followed by a regression where nearshore deposits

(sandstone lithosome) of the Icebox Formation retreated as far basinward as northeastern North Dakota. The retreat of the sea was followed by another transgression, as signified by the shale of the Icebox overlying the sandstone of the Icebox lithosome. The intertonguing of sandstone and shale suggests that a facies relationship exists, at least in part, between the upper member of the Black Island Formation and the Icebox Formation.

The Icebox sandstone lithosome in Grand Forks County may be an offshore bar deposit. The "Carman sandstone," described in Andrichuk (1959), occurs as a long, narrow sandstone body within the shale of the Winnipeg (his "upper unit") in southern Manitoba; it was interpreted by Vigrass (1971) to be an offshore deposit which was deposited up to 160 km (100 mi) from shore. Like the "Carman sandstone body," the sandstone lithosome within the Icebox Formation in Grand Forks County is a well-sorted, commonly argillaceous, friable sandstone. Both sandstone bodies are elongate, with the long axis oriented east-west. The similarities between the Carman and Grand Forks County sandstone bodies suggest that they may have been deposited under similar conditions.

The third Icebox sandstone, located in southwestern North Dakota, has not been cored; the log responses indicate that the unit consists of interbedded sandstone and shale. The orientation of this lithosome and the interbedding of the sandstone and shale suggest that this may be a deltaic deposit with a source to the south.

Roughlock Formation: The Roughlock Formation is also interpreted to have been deposited in an offshore environment. The rich and diverse faunal assemblage within this formation, which includes brachiopods, echinoderms and trilobite fragments, indicates deposition in an open-marine environment with normal salinities. The environmental conditions in which the Roughlock was deposited appear to be similar to those of the Icebox Formation (offshore) except for a decrease in the amount of detrital input, which allowed the production of the carbonates of the Roughlock.

The lobate shape of the Roughlock sandstone lithosome and its interbedded sandstones and shales suggest that it may have a deltaic origin. The Roughlock sandstone lithosome is similar in lithology and in morphology to the sandstone lithosome of the Icebox Formation in southwestern North Dakota. The Roughlock sandstone lithosome is stratigraphically higher than the sandstone lithosome of the Icebox and parts of the two are stacked in a portion of south-central North Dakota. It is possible that these two sandstone lithosomes are genetically related, and the Roughlock lithosome represents a later shift of the deltaic distributaries to the east.

SUBSIDENCE HISTORY

The timing, location, and mechanism for the initiation of subsidence in the Williston Basin have been the subjects of discussion by various workers. Carlson (1960) suggested that initial subsidence took place at approximately the time that deposition of the Winnipeg Group began. Carlson and Anderson (1965) placed the time of initiation sometime during the interval from Middle Ordovician to Early Devonian. Lochman-Balk and Wilson (1967) placed the origin in earliest Ordovician time, and considered the earliest depocenter to have been along what is now the Montana-North Dakota border, in southern McKenzie County. Gerhard et al (1982) dated the basin as a structural depression from Middle Ordovician time, and suggested that the basin may have had its origin as a depressed block between two pre-Phanerozoic left-lateral shear zones. In this view, the initial and all significant subsequent basin movements would be related to major orogenic events elsewhere in North America. Ahern and Mrkvicka (1984) considered the basin to have originated during the middle Ordovician, and to have resulted from thermal contraction of the lithosphere. Crowley et al (1985) elaborated on the hypothesis of Ahern and Mrkvicka and concluded that the most likely cause of a thermal anomaly was upwelling or diapirism of asthenosphere into lithosphere. Fowler and Nisbet (1985) maintained that the Williston Basin began to subside in Cambrian time, and proposed that the subsidence was due to a phase change transformation of a mafic subcrustal body to eclogite. Although we cannot shed any light on questions about mechanisms of formation of the basin, our interpretation places some constraints on initiation and location of subsidence, and, at present, is the best description which can be made of the tectonic history of the basin during the Deadwood-Winnipeg interval.

With the available data, we have approached the question of timing of the onset of basin subsidence in two ways: 1) the construction of isopach maps of individual members of the Deadwood Formation, including only those control points where the overlying member was also present; and 2) construction of backstripping curves for the Deadwood-Winnipeg interval.

It has long been recognized that this isopach pattern of the Deadwood is due at least in part to erosion during the 30-40 million years of exposure between the end of Deadwood sedimentation and the onset of Winnipeg deposition. Some workers have attributed the pattern entirely to erosion, and maintained that subsidence of the basin began about the time Winnipeg deposition began. As the upper four members of the Deadwood Formation are apparently comformable, it should be possible to test for subsidence by examining each member where it clearly has not been eroded significantly, that is, where it is overlain by the next higher member. Such maps were constructed for members C, D and E. The isopach map for member D (Fig. 6b) shows an elongate area of increased thickness in western North Dakota, at least 10-15 m thicker than the surrounding areas. The member C isopach map (Fig. 6a) also has a pattern suggestive of such thickening. In the latter case, however, the thickening is due largely to one very thick section in Billings County and may reflect irregularities on top of members B and A and not any subsidence. The isopach of member E (Fig. 6c) also shows some thickening, although the thickness of the member where it is overlain by Member F can be determined in only 13 wells and there are probably too few control points to generate a meaningful map.

Backstripping techniques (e.g. Sclater and Christie, 1980) calculate the tectonic component of subsidence by decompaction of sedimentary units to their thicknesses immediately after deposition, and by removal of the subsidence due to sediment loading. Corrections are also necessary for any eustatic changes in sea level; we used the Phanerozoic sea-level curves of Vail et al (1977). We have also followed the suggestion of Bond and Kominz (1984), in expressing tectonic subsidence in terms of two compaction models: 1) except for shales, porosity loss is assumed to be due entirely to cementation (minimum compaction); and 2) porosity loss is due entirely to compaction (maximum compaction). This results in two curves representing the two extreme cases in porosity loss and provides us with limits on the subsidence models.

There are some difficulties, however, in applying these techniques to the Deadwood-Winnipeg interval in the Williston Basin. First, there is some uncertainty about the ages of the strata involved, especially within the Deadwood Formation.

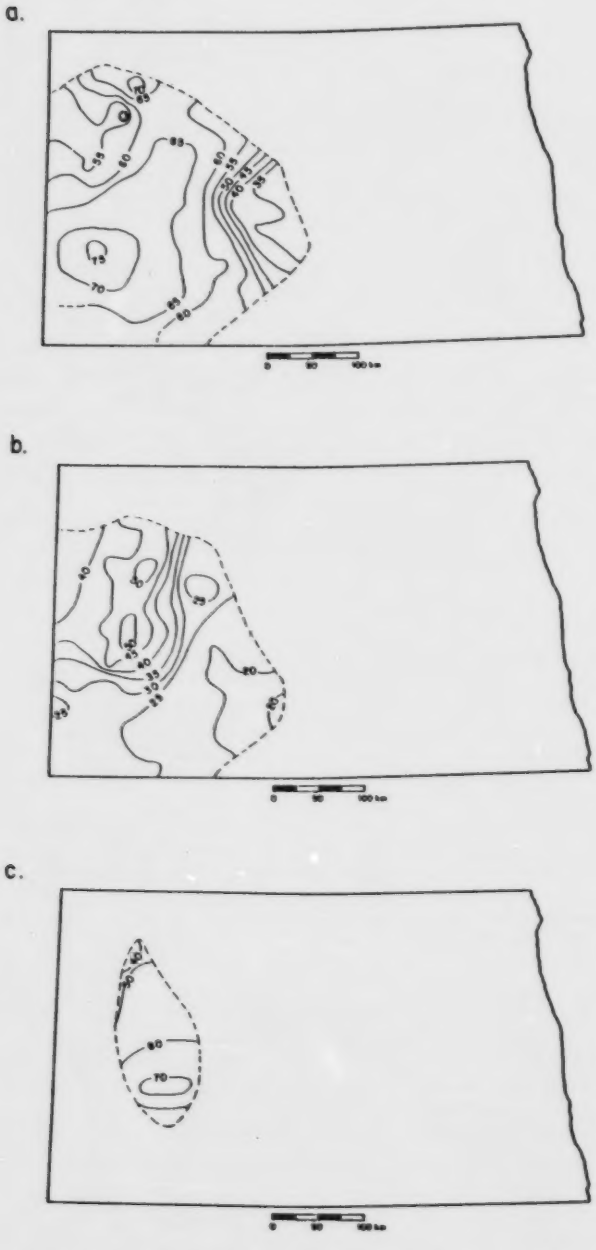


Fig. 6 Isopach maps of members of the Deadwood Formation where they are overlain by the next highest member (dashed lines represent erosional limits of the members). a) Isopach map of member C where it is overlain by member D (contour interval = 5 m); b) Isopach map of member D where it is overlain by member E (contour interval = 5 m); c) Isopach map of member E where it is overlain by member F (contour interval = 10 m).

We have extrapolated the ages given by Lochman (1964a, 1964b, 1966) and Lochman-Balk and Wilson (1967) for correlative rocks in Montana and North Dakota, but there are too few useful fossils in the available cores for us to date the Deadwood section with certainty. The Deadwood ages assigned here (Fig. 8) are probably the best estimates with the currently available data, but there is considerable room for improvement in their precision. The ages for the Winnipeg (after Thompson, 1984) are much more reliable. Second, the amount of calculated subsidence depends in part on the relative position of the unit at the time of deposition with respect to sea level. The eustatic sea level curves of Vail et al (1977) are the best synthesis of the changes in sea level though the Phanerozoic but, as their data have never been made public, it is impossible to evaluate the precision, magnitude, or global extent of the sea level changes they showed, especially for the early Paleozoic (Watts, 1982; Miall, 1986). Therefore, the exact amount of subsidence for a given time interval cannot be reliably estimated. Thirdly, estimates of the rate of subsidence depend upon knowing the time interval involved. The absolute ages we have used for the Cambrian and Ordovician epoch boundaries (the basis for the horizontal axes of the diagrams) are those given in Harland et al (1982), and are probably the best available, although Harland et al (p. 51) described the control for these particular dates as poor. With these qualifications, it is probably best not to treat the backstripping results as having high precision (e.g. a subsidence rate of 11.34 m/my), but to consider the curves as indicators of relative rates of subsidence.

Four backstripping curves are illustrated in Figure 7. They illustrate the important features shown by nearly all of the curves which cover both the Deadwood and Winnipeg. First, during deposition of members A and B, there was little, if any, tectonic subsidence; only a few wells, such as NDGS 6228, show any significant movement during this interval. During member C deposition, there was a moderate rate of subsidence, generally greater than any earlier rate. Beginning with the interval represented by member D, the subsidence rate increased sharply, and remained high for the remainder of the Deadwood time. There are no data for the 30-40 million year gap between the Deadwood Formation and the Winnipeg Group, but, as the Winnipeg Group also shows a high rate, it may well be that subsidence continued at that rate throughout the intervening time.

On the basis of the isopach maps and backstripping curves, it seems possible to place the beginning of Williston Basin subsidence at a time no later than during deposition of member D of the Deadwood Formation (late Tremadocian), and perhaps even earlier; the isopach pattern and backstripping of member C are suggestive, and may indicate an initiation during member C time. The initial subsidence may have been elongate, as shown on the member D isopach (Fig. 6b) rather than circular, perhaps indicating graben formation as the first subsidence event. We place the origin of the basin significantly earlier than indicated by previous studies, with the exception of Lochman-Balk and Wilson (1967) and Fowler and Nisbet (1985), although the latter study dated the initial subsidence earlier than our evidence indicates. It does not appear that the initial subsidence was associated with significant tectonic activity in other parts of North America (as suggested by Gerhard et al, 1982), as no major orogenic events seem to have taken place between the Tremadocian and Ashgillian, when the Taconic orogeny occurred. The subsidence seems to have continued at roughly the same rate throughout the remainder of Deadwood and Winnipeg deposition.

By early Late Ordovician time (early Caradocian), when the Black Island Formation began to be deposited, subsidence of the basin was well under way. The area of greatest subsidence had become circular rather than retaining the earlier elongate form (compare Figs. 6b and 5c), and the center of subsidence seems to have shifted somewhat northward. Both the relatively rapid rate of subsidence and the location of the center of subsidence seem to have remained constant throughout Winnipeg time (until mid-Caradocian).

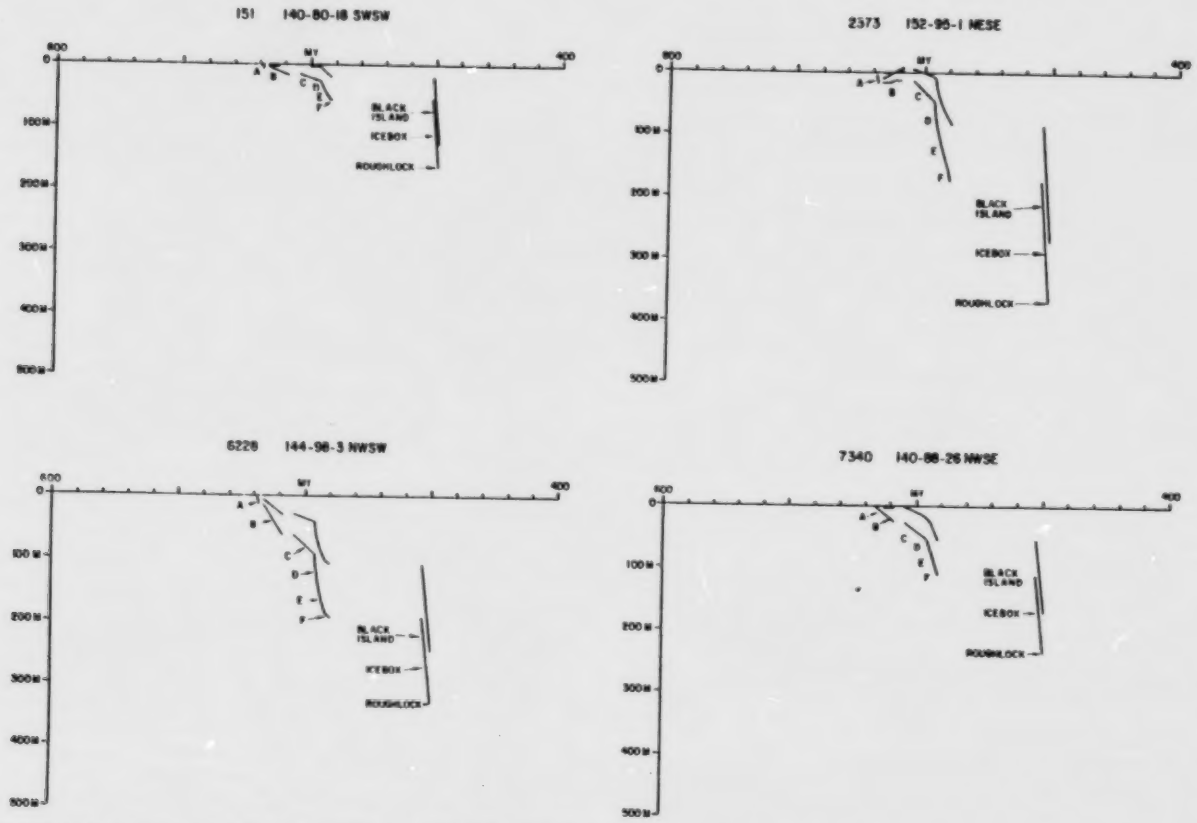


Fig. 7 Backstripping curves from four wells. The curves shown are the calculated amounts of tectonic subsidence (vertical scale) for minimum (upper) and maximum (lower) compaction. Labelled portions of curves represent subsidence during deposition of corresponding formation or member.

DEPOSITIONAL HISTORY

Until the latter part of Cambrian time, the area now occupied by North Dakota was exposed to erosion and developed a surface of considerable relief. The area was first covered by the Cambrian transgression during Dresbachian time; deposition around islands of Precambrian basement produced an erratic distribution of facies, with reworking of possible fluvial conglomerates in a nearshore marine environment, and deposition of the quartz arenites and glauconitic quartz arenites of member A.

Regression of the Dresbachian sea was followed by erosion and weathering, producing an unconformity on top of member A. There were two transgressive-regressive events on the craton during Franconian and Trempealeauan time, during which deposition of member B occurred; the glauconitic siltstones were probably deposited in a nonturbulent offshore to marginal marine setting. There may be an unconformity within the B member caused by these changes in sea level.

During the late Trempealeauan to early Tremadocian, the sea advanced again, and a prograding shoreline facies (member C) was deposited during the early to middle Tremadocian. During the early part of member C deposition, the erosional surface on the Precambrian basement in North Dakota was completely submerged for the first time. Regression commenced during deposition of member C, shifting the shoreline as far west as eastern Montana.

A rapid transgression during middle Tremadocian resulted in reworking of shoreline sands in a more distal high-energy carbonate buildup (upper C member). The approximate limit of shoreline retreat is in southern North Dakota, where quartz arenites comprise the upper portion of member C. This was followed (late Tremadocian to early Arenigian) by progradation of offshore to lower shoreface (member D) and upper shoreface (lower arenites of member E) deposits over the marginal limestones, and the beginning of another regression during progradation.

Another transgression in early Arenigian time deposited the marginal limestones of upper member E over the quartz arenites of the lower member E, with reworking of clean sands in high-energy environments. This was followed by progradation of offshore to lower shoreface silts (upper E) and upper shoreface arenites (F member) over the marginal limestones, coincident with another regression.

At the end of the Early Ordovician (latest Llanvirnian), there was a major eustatic sea level drop, and marine deposition in North Dakota ceased. The basin continued to subside, however, and Deadwood strata were eroded from the newly exposed areas of the basin. Although it can only be inferred from the direction of transgression and regression, the drainage direction during this time was probably to the south and west.

It is uncertain how great a thickness of Deadwood strata was eroded during this interval of exposure. On the basis of thickness differences, we estimate that at least 30 m (100 ft) of Deadwood were eroded from the margins of the basin, and perhaps as much as 180 m (590 ft) from the basin center, above

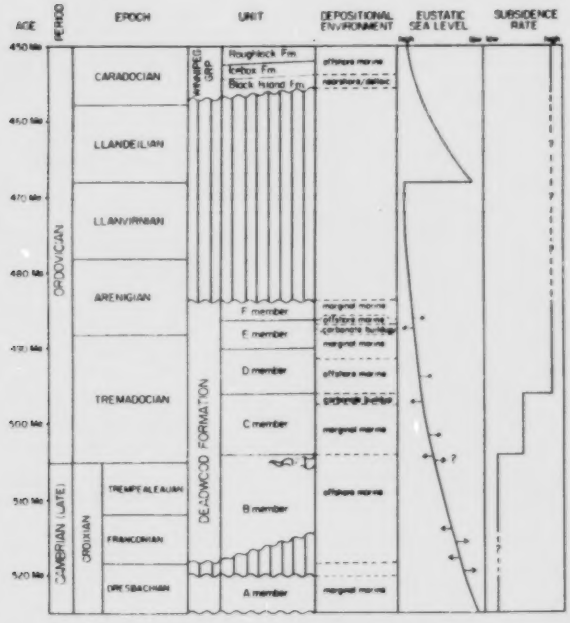


Fig. 8 Summary diagram of tectonic and depositional history of the Deadwood and Winnipeg. Absolute ages are from Harland et al (1982). Sea level curve is after Vail et al (1977); arrows indicate short-term transgressions and regressions.

the top of the F member in western North Dakota. The latter estimate is based on the fact that, during the interval between the deposition of the highest preserved strata of member F and the major eustatic drop in sea level (middle and late Arenigian to late Llanvirnian), two transgressive-regressive events occurred in Canada (Barnes, 1984, p. 58). Similar events in North Dakota earlier in Deadwood time resulted in deposition of 50-90 m (165-295 ft) of sedimentary rocks with each transgression and regression.

By late Ordovician time (early Caradocian), sea level was rising again. The first indication of this in North Dakota was the deposition of the Black Island delta plain deposits in western North Dakota, which were probably building out to the south and west. The fact that the lower Black Island strata can only be distinquished in western North Dakota suggests that this was the lowest-lying area at the time, and that the area was subsiding. The fluvial systems feeding the delta or deltas were probably draining the higher areas to the north and east, eroding the Deadwood and the Precambrian basement. With continued sea level rise, the deltaic deposits were covered, and the shallow marine sandstones of the upper Black Island were deposited. With continued sea level rise, the rocks of the upper Black Island were deposited farther east, and deposition of the shales of the Icebox Formation commenced in western North Dakota. The transgression proceeded far enough by the end of Black Island time that the entire area now occupied by North Dakota was submerged and deposition of the Icebox shales was widespread.

Roughlock deposition followed (middle Caradocian), and was rapid by comparison with earlier Winnipeg deposition. The Roughlock grades upward into the Red River Formation, and the considerably greater thickness of the Roughlock in the eastern part of North Dakota than the western part indicates that some argillaceous sediment was still being supplied to the eastern part of North Dakota after the cleaner carbonates of the Red River had begun to be deposited farther west.

CONCLUSIONS

1) On the basis of well log parameters and analysis of cores, the Deadwood Formation in the subsurface of the Williston Basin in North Dakota is divisible into six correlatable lithostratigraphic units. These units are here informally described as members of the Deadwood Formation, and labelled, in ascending order, A through F.

2) The Deadwood Formation consists largely of siliciclastic rocks, principally quartz arenites, quartz wackes, and siltstones, and lesser amounts of carbonate rocks, with textures from mudstones to grainstones.

3) Member A was deposited under marginal marine, probably beach, conditions. Most of member B formed under quieter, probably more offshore, conditions. The upper portion of member B through member F consist of repetitive sequences representing transitions from a distal carbonate buildup to a marginal marine environment. The lower carbonate mudstone-grainstone lithologies were separated from the coastal siliciclastics by a broad shallow shelf.

4) The Winnipeg Group consists of three formations: in ascending order, the Black Island, Icebox, and Roughlock Formations. The Black Island Formation is composed of sandstones with subordinate amounts of shale, and represents fluvial/deltaic deposition in the lower part, which occurs only in western North Dakota, and shallow marine deposition in the upper part. The Icebox Formation is largely shale, with some local sandstone lithosomes, and was deposited in a deeper marine environment than was the Black Island. The Roughlock consists of argillaceous, fossiliferous limestone, and was also deposited in a deeper marine environment. The three formations are, in part, lateral facies equivalents.

5) The initial subsidence of the Williston Basin in North Dakota occurred at a time no later than during deposition of Member D of the Deadwood Formation (late Tremadocian), and perhaps even earlier. It does not appear to have been associated with major orogenic events elsewhere in North America. The area of greatest subsidence seems to have been initially elongate, and to have become more circular by Winnipeg time.

6) The Deadwood Formation was deposited during a gradual major eustatic sea level rise, which included several small-scale transgressive-regressive episodes.

7) At the end of the Early Ordovician (latest Llanvirnian), there was a major eustatic sea level drop, and marine deposition in North Dakota ceased. Deadwood strata were eroded from the newly exposed areas of the basin. The drainage direction was probably to the south and west. A thickness of at least 30 m (100 ft), and perhaps as much as 180 m (590 ft), was eroded from the Deadwood Formation during exposure.

8) By Late Ordovician time (early Caradocian), sea level was rising again. In North Dakota, the first evidence is the fluvial-deltaic deposits of the lower Black Island Formation, which were deposited in the area where the greatest amount of subsidence had taken place. With continued sea level rise, the deltaic deposits were covered, and the shallow marine sandstones of the upper Black Island were deposited, followed by the deeper marine shales of the Icebox Formation and, finally, by the argillaceous limestones of the Roughlock Formation.

ACKNOWLEDGEMENTS

This paper was drawn in part from M.Sc. thesis research on the Deadwood Formation (Anderson) and Winnipeg Group (Thompson), conducted at the University of North Dakota by the junior authors, under the direction of the senior author.

The majority of the drafting was done by Ken Dorsher and Julie LeFever.

REFERENCES CITED

Ahern, J.L., and Mrkvicka, S.R., 1984, A mechanical and thermal model for the evolution of the Williston Basin: Tectonics, v. 3, p. 79-102.

Andrichuk, J.M., 1959, Ordovician and Silurian stratigraphy and sedimentation in southern Manitoba, Canada: AAPG Bull., v. 43, p. 2333-2398.

Barnes, C.R., 1984, Early Ordovician eustatic events in Canada: In: Bruton, D.L., (ed.), Aspects of the Ordovician System: Paleontological Contributions from the University of Oslo, No. 295, Universitets-forlaget, p. 51-63.

Bond, G.C., and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning: Geol. Soc. America Bull., v. 95, p. 155-173.

Brett, C.E., Liddell, W.D., and Derstler, K.L., 1983, Late Cambrian hard substrate communities from Montana/Wyoming: The oldest known hardground encrusters: Lethaia, v. 16, p. 281-289.

Butler, R.J., Battin, R.L., Plank, R.F., and Winston, G.O., 1955, Lithologic correlation of Middle and Lower Paleozoic rocks: In: North Dakota Geol. Soc., Black Hills Field Conference, p. 38-42.

Carlson, C.G., 1958, The stratigraphy of the Deadwood-Winnipeg interval in North Dakota and northwestern South Dakota: In: Saskatchewan Geol. Soc. and North Dakota Geol. Soc., Second International Williston Basin Symposium, Regina, p. 20-26.

Carlson, C.G., 1960, Stratigraphy of the Winnipeg and Deadwood Formations in North Dakota: North Dakota Geol. Surv. Bull. 35, 149. p.

Carlson, C.G., 1964, Facies relationships of the Winnipeg Group in eastern North Dakota: In: Leskela, W., Brindle, J., and Harris, S.H., Third International Williston Basin Symposium, Billings Geol. Soc., North Dakota Geol. Soc., and Saskatchewan Geol. Soc., p. 45-50.

Carlson, C.G. and Anderson, S.B., 1965, Sedimentary and tectonic history of North Dakota part of the Williston Basin: AAPG Bull., v. 49, p. 1833-1846.

Crowley, K.D., Ahern, J.L., and Naeser, C.W., 1985, Origin and epeirogenic history of the Williston Basin: Evidence from fission-track analysis of apatite: Geology v. 13, p. 620-623.

Darton, N.H. and Paige, S., 1925, Description of the central Black Hills: U.S. Geol. Surv. Geological atlas of the United States, Central Black Hills Folio 219, 34 p.

Driese, S.G., Byers, C.W., and Dott, R.H., Jr., 1981, Tidal deposition in the basal Upper Cambrian Mt. Simon Formation in Wisconsin: Jour. Sed. Petrology, v. 51, p. 367-381.

Fowler, C.M.R., and Nisbet, E.G., 1985, The subsidence of the Williston Basin: Can. Jour. Earth Sci., v. 22, p. 408-415.

Fuller, J.G.C.M., 1961, Ordovician and contiguous formations in North Dakota, South Dakota, Montana and adjoining areas of Canada and the United States: AAPG Bull., v. 45, p. 1334-1363.

Fuller, J.G.C.M., and Porter, J.W., 1962, Cambrian, Ordovician, and Silurian formations of the northern Great Plains, and their regional connection: Alberta Soc. Petr. Geol. Jour., v. 10, p. 445-485.

Furnish, W.M., Barragy, E.J. and Miller, A.K., 1936, Ordovician fossils from the upper part of the type section of the Deadwood formation, South Dakota: AAPG Bull., v. 20, p. 1329-1341.

Fyson, W.K., 1961, Deadwood and Winnipeg stratigraphy in southwestern Saskatchewan: Saskatchewan Dept. Min. Res. Rept. 64, 37. p.

Genik, G.J., 1954, A regional study of the Winnipeg formation: Alberta Soc. Petr. Geol. Jour., v. 2, p. 1-5.

Gerhard, L.C., Anderson, S.B., LeFever, J.A., and Carlson, C.G., 1982, Geological development, origin, and energy mineral resources of Williston basin, North Dakota: AAPG Bull., v. 66, p. 989-1020.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., and Walters, R., 1982, A geologic time scale: Cambridge University Press, Cambridge, 131 p.

Hiscott, R.N., James, N.P., and Pemberton, S.G., 1984, Sedimentology and ichnology of the Lower Cambrian Bradore Formation, coastal Labrador: fluvial to shallow-marine transgressive sequence: Canadian Petrol. Geol. Bull., v. 32, p. 11-26.

Kulik, J.W., 1965, Stratigraphy of the Deadwood Formation, Black Hills, South Dakota and Wyoming: unpub. Master of Science thesis: South Dakota School of Mines and Technology, Rapid City, 263 p.

Kupsch, W.O., 1953, Ordovician and Silurian stratigraphy of east-central Saskatchewan; Saskatchewan Geol. Surv. Rept. 10, 62 p.

Ladle, G.H., 1972, The sedimentary petrography and sedimentation of the Deadwood Formation in the Black Hills, South Dakota: unpub. Master of Science thesis: University of Houston, 179 p.

Lochman, C., 1964a, Upper Cambrian faunas from the subsurface Deadwood Formation, Williston Basin, Montana: Jour. Paleo., v. 38, p. 33-60.

Lochman, C., 1964b, Basal Orodvician faunas from the Williston Basin, Montana: Jour. Paleo., v. 38, p. 453-476.

Lochman, C., 1966, Lower Ordovician (Arenig) faunas from the Williston Basin, Montana and North Dakota: Jour. Paleo., v. 40, p. 512-548.

Lochman-Balk, C., and Wilson, J.L., 1967, Stratigraphy of Upper Cambrian-Lower Ordovician subsurface sequence in Williston Basin: AAPG Bull., v. 51, p. 883-917.

Lochman, C., and Duncan, D., 1950, The Lower Ordovician Bellenfontia fauna in central Montana: Jour. Paleo., v. 24, p. 350-353.

Macauley, G., 1955, A general discussion of the Winnipeg Formation: Alberta Soc. Petr. Geol. Jour., v. 3, p. 49-59.

McCabe, H.R., 1978, Reservoir potential of the Deadwood and Winnipeg Formations in southwest Manitoba: Manitoba Dept. Mines Geol. Paper 78-3, 54 p.

McCoy, M.R., 1952, Ordovician sediments in the northern Black Hills: In: Sonnenberg, F.P., (ed.), 3rd Annual Field Conf. Guidebook, Billings Geol. Soc., p. 44-47.

McCoy, M.R., 1958a, Cambrian of the Power River Basin: In: Strickland, J.W., (ed.), Power River Basin, 13th Annual Field Conf. Guidebook, Wyoming Geol. Assoc., p. 21-24.

McCoy, M.R., 1958b, Ordovician rocks of the northern Powder River Basin and Black Hills Uplift areas, Montana, Wyoming, and South Dakota: In: Strickland, J.W., (ed.), Powder River Basin, 13th Annual Field Conf. Guidebook, Wyoming Geol. Assoc., p. 25-29.

McLean, D.D., 1960, Deadwood and Winnipeg stratigraphy in east-central Saskatchewan: Saskatchewan Dept. Min. Res. Rept. 47, 37 p.

Miall, A.D., 1986, Eustatic sea level changes interpreted from seismic stratigraphy: A critique of the methodology with particular reference to the North Sea Jurassic record: AAPG Bull., v. 70, p. 131-137.

Parks, T. and Amber, J.S., 1956, Winnipeg and older rocks, Saskatchewan: In: First International Williston Basin Symposium, Bismarck, North Dakota, p. 115-120.

Paterson, D.F., 1971, The stratigraphy of the Winnipeg Formation (Ordovician) of Saskatchewan: Saskatchewan Dept. Min. Res. Rept. 140, 57 p.

Porter, J.W., and Fuller, J.G.C.M., 1958, Succession of Lower Paleozoic in the northern part of the Williston Basin: In: Saskatchewan Geol. Soc. and North Dakota Geol. Soc., Second International Williston Basin Symposium, Regina, p. 33-39.

Reineck, H.E. and Singh, I.B., 1980, Depositional sedimentary environments: New York, Springer-Verlag, 549 p.

Ross, R.J., 1957, Ordovician fossils from wells in the Williston basin, eastern Montana: U.S. Geol. Surv. Bull. 1021, part M, p. 439-510.

Ross, R.J., 1976, Ordovician sedimentation in the western United States: In: Bassett, M.G., (ed.), The Ordovician System: Cardiff, Wales, Proceedings of a Palaeontological Association Symposium, p. 73-105.

Sclater, J.G., and Christie, P.A.F., 1980, Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the central North Sea basin: Jour. Geophys. Res., v. 85, p. 3711-3739.

Sepkoski, J.J., Jr., 1982, Flat pebble conglomerates, storm deposits, and the Cambrian bottom fauna: In: Einsele, G., and Seilacher, A. (eds.), Cyclic and event stratification: Springer-Verlag, New York, p. 371-385.

Stanley, T.M., 1984, Stratigraphy, ichnology, and paleoichnology of the Deadwood Formation (Upper Cambrian-Lower Ordovician), northern Black Hills, South Dakota: unpub. Master of Science thesis, Kent State University, Ohio, 224 p.

Steece, F.V., 1978, Deadwood Formation in the Williston Basin, South Dakota: In: Estelle, D., and Miller R. (eds), The economic geology of the Williston Basin, Montana Geol. Soc., Williston Basin Symposium, Billings, p. 63-69.

Thompson, S.C., 1984, Depositional environments and history of the Winnipeg Group (Ordovician), Williston Basin, North Dakota: unpub. Master of Science thesis, University of North Dakota, Grand Forks, 210 p.

Turner, P., 1980, Continental red beds: Amsterdam, Elsevier Scientific Publishing Company, 562 p.

Vail, P.K., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level: In: Payton, E.D., (ed.), Seismic stratigraphy — Applications to hydrocarbon exploration, AAPG Memoir 26, p. 83-97.

Vigrass, L.W., 1971, Depositional framework of the Winnipeg Formation in Manitoba and eastern Saskatchewan: Geol. Assoc. Canada Spec. Paper 9, p. 225-234.

Watts, A.B., 1982, Tectonic subsidence, flexure and global changes of sea level; Nature, v. 297, p. 469-474.

THE WINNIPEGOSIS FORMATION OF THE NORTHEASTERN MARGIN OF THE WILLISTON BASIN

L. R. ROSENTHAL

Department of Geology
Brandon University
Brandon, Manitoba, Canada
R7A 6A9

INTRODUCTION

Recent significant oil discoveries in the Winnipegosis Formation in the Tableland area of southern Saskatchewan have prompted a re-evaluation of the existing models for predicting the distribution of porosity within this interval in the northern part of the Williston Basin. This study compiles a series of observations from outcrop exposure and diamond drill cores of Winnipegosis strata in the Manitoba outcrop belt and proposes a depositional/diagenetic model which might aid explorationists working in the subsurface.

STRATIGRAPHIC FRAMEWORK

The Devonian which lies in most of the Williston Basin is exposed in a wide belt which trends northwesterly across central Manitoba (Fig. 1). Most of the Paleozoic nomenclature used in the Williston Basin is derived from important quarry or outcrop sections in this area. A complete review of the stratigraphic nomenclatural schemes for the Devonian section is given in Morris et al (1982) and the terminology used in the report is depicted in Figure 2.

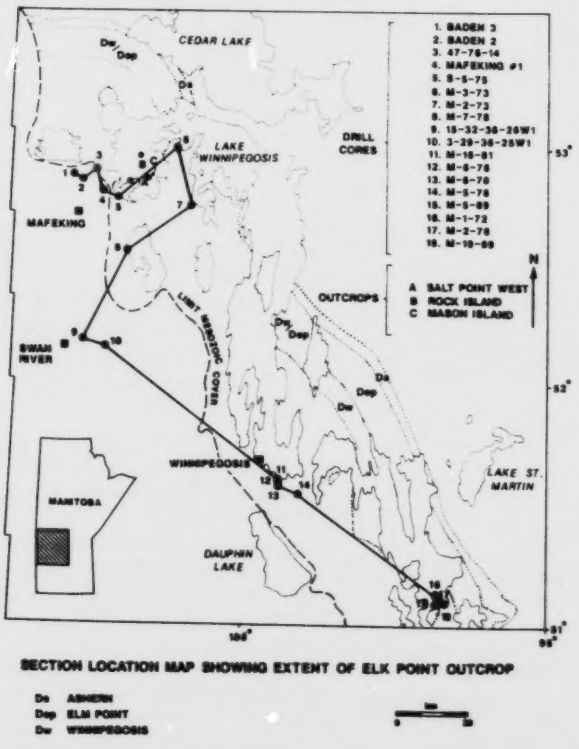


Fig. 1 Location map.

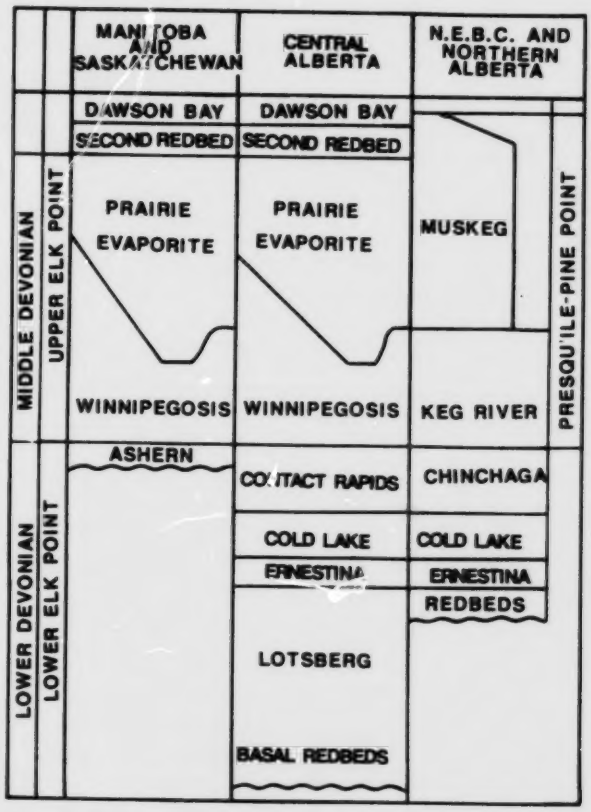


Fig. 2 Stratigraphic correlation chart.

The term Elk Point was first introduced by McGehee (1949) to describe Middle Devonian strata of east-central Alberta. Baillie (1951, 1953) extended the Elk Point terminology into the Manitoba outcrop belt and proposed that this unit be subdivided into the Ashern, Elm Point, Winnipegosis and Prairie Evaporite Formations. The Prairie Evaporite is not present in the Manitoba outcrop belt but a collapse breccia at the top of the Winnipegosis carbonate suggests that the salt once covered a much larger area than at present.

REGIONAL SETTING

The Winnipegosis buildups studied in this report were deposited in a relatively deep marine basin which flanked a broad carbonate platform in what is now central Manitoba. These carbonates were deposited during the initial phase of the Kaskaskia transgression (Perrin, 1982). The geometry of this basin can be discerned from an isopach map of the Winni-

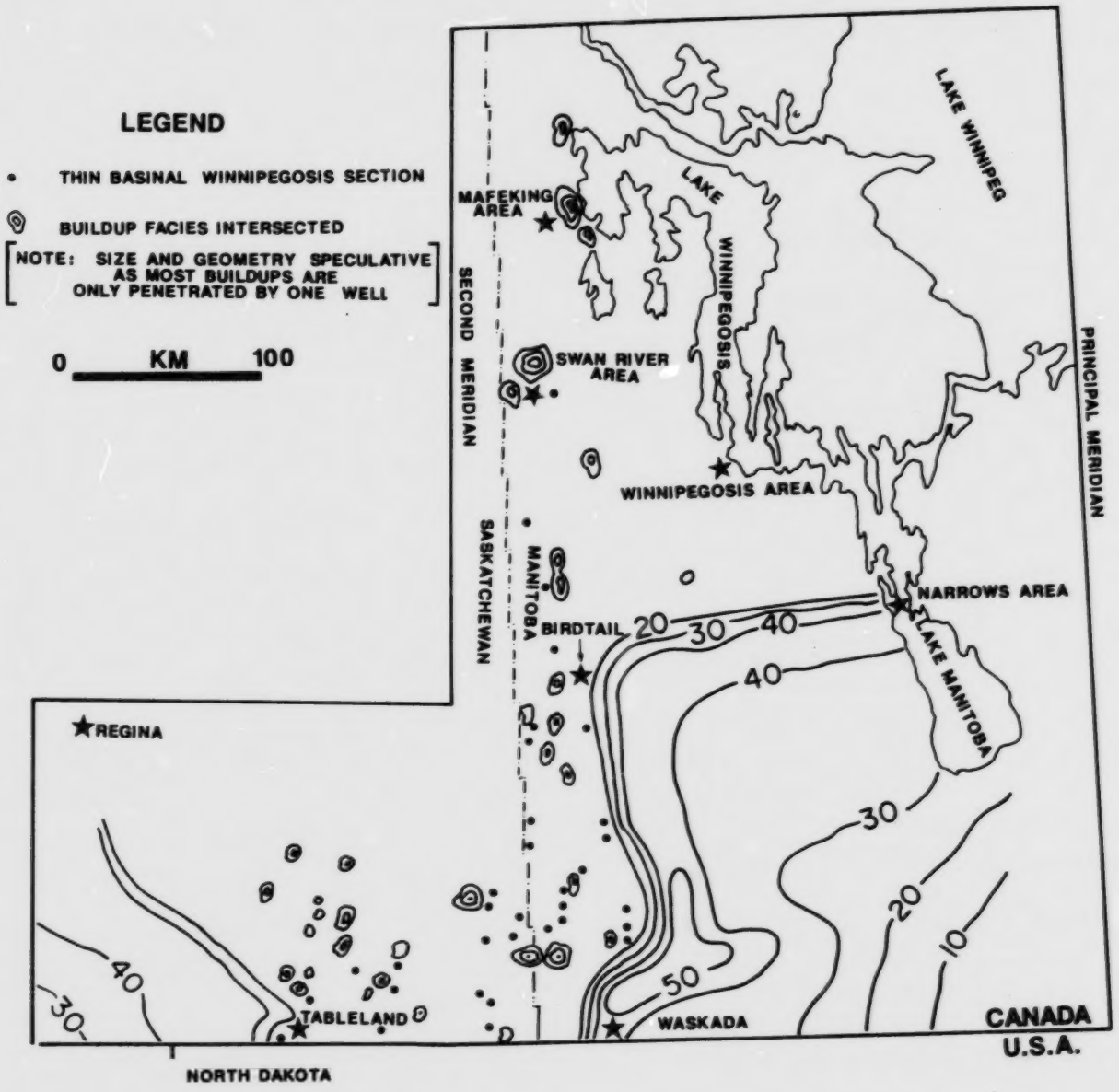


Fig. 3 Isopach map of Winnipegosis carbonate (contour interval = 10 m).

pegosis (Fig. 3) which has been compiled from unpublished Manitoba Mines Branch reports and information obtained from the present study. The abrupt platform-basin boundary, termed the Birdtail-Waskada axis by McCabe (1967), trends northwards from a point on the International Boundary approximately 20 miles east of the Manitoba-Saskatchewan border. Approximately 100 miles to the north, the bank edge turns abruptly east and presumably crops out just south of the Narrows of Lake Manitoba (Fig. 3). All the cores and outcrops examined in this study were located north of this bank as none is known from the bank complex to the south. An other important feature is the regional southeasterly attenuation of the unit onto the Transcontinental Arch of North Dakota (Fig. 3).

PREVIOUS SEDIMENTOLOGICAL INVESTIGATIONS

The earliest studies of Devonian strata in Manitoba were concerned primarily with basic description and regional correlation of the units (Tyrrell, 1982). Baillie's (1951, 1953) classic reports were the first attempts to interpret the depositional environments of the various stratigraphic units. He recognized massive-bedded yellowish grey dolomitized biohermal reefs separated by well bedded saccharoidal dolomites which locally exhibited high-angle (20°) stratification. McCabe (1967) compiled a series of regional isopach maps of the Devonian and recognized the Birdtail-Waskada axis, which marked the western limit of the Winnipegosis platform facies

and which later served to focus post-Elk Point salt solution. During the next decade, most sedimentological studies took place in southern and central Saskatchewan where the numerous drill cores available provided a large data base (Jones, 1965; Wardlaw and Reinson, 1971; Kendall, 1975; Fuzesy, 1975; Gendzwill, 1978). All these workers noted the paucity of organic framework in the buildups and proposed that they be termed either banks (Kendall, 1975) or mud mounds (Gendzwill, 1978) rather than true reefs. Norris et al (1982) compiled outcrop and diamond core data of the Manitoba outcrop belt and plotted the distribtuion of reef and inter-reef facies within the Winnipegosis Formation. They also noted that the Birdtail-Waskada axis was approximately coincident with, and probably related to, the tectonic boundary between the Archean Superior and Proterozoic Churchill provinces (Norris et al, 1982).

In North Dakota, Perrin (1982) documented the presence of shelf, pinnacle reef and basin facies within the Winnipegosis. Moreover, she suggested that a dramatic eustatic drop in sea level had led to exposure and dolomitization of the reefs, and to formation of intertidal to shallow-subtidal stromatolites in the tidal flats of the inter-reef areas.

METHODOLOGY

This report is a synthesis of data and interpretations gleaned from a study of four outcrop exposures and eighteen diamond drill holes which penetrated most or all of the Winnipegosis within the outcrop belt of Manitoba. The cores were described using the terminology of Embry and Klovan (1971), and acetate peels and thin sections were examined to define the microfacies and document the diagenetic history.

The cores were collected by the Manitoba Mines Branch between 1968 and 1985 as part of a stratigraphic mapping and industrial minerals evaluation program. They are stored at the Brady Road and University of Manitoba core sheds of the Manitoba Mines Branch and were logged between September 1985 and June of 1986. Figure 1 shows the location of the cores and outcrops described in the study.

CORE STUDY

Four distinct lithostratigraphic units are recognized. These are, in ascending order, the Ashern Formation, the Lower Winnipegosis member, the Upper Winnipegosis member, and the Prairie Evaporite residual clay horizon. Within these lithostratigraphic units, eight depositional facies were identified on the basis of primary textures. Two additional diagenetic facies which retained no relict depositional textures were also recognized. The relationship between lithostratigraphic units and depositional/diagenetic facies is shown in the cross-section (Fig. 4) and on the composite sketch (Fig. 5).

ASHERN FORMATION

FACIES 1: GREY-GREEN DOLOMITIC SHALE

The Ashern Formation consists of a thin (0.5 to 5.0 m) green dolomitic shale which unconformably blankets a brick-red paleosol on a brecciated post-Silurian exposure surface. In some cores (M-6-76), the contact is abrupt whereas in others, a red-green mottled heterolithic intraclast conglomerate up to 5 m in thickness is present below the Ashern Shale. Hematite staining adjacent to fractures and around the margins of angular clasts suggests that at least some of the staining is late

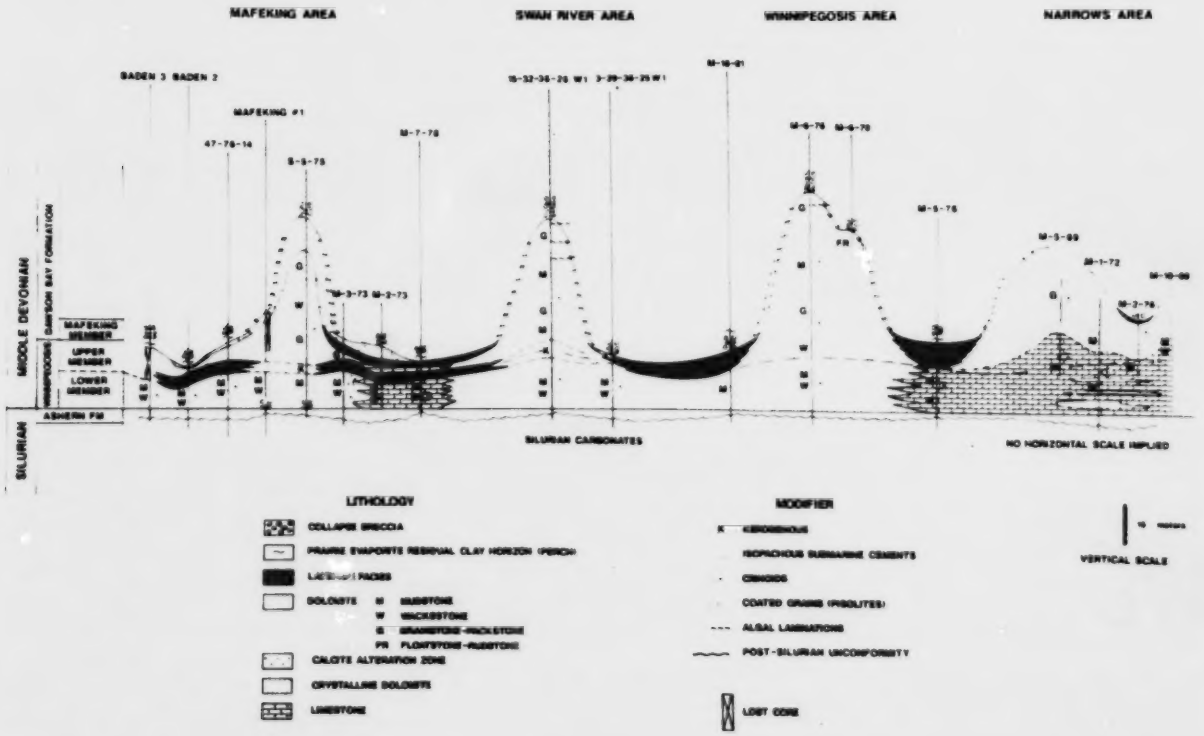


Fig. 4 Stratigraphy and facies correlation diagram of the Winnipegosis Formation in central Manitoba.

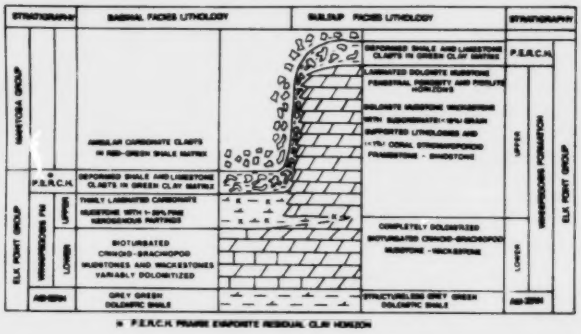

STRATIGRAPHY
BASINAL FACIES LITHOLOGY
BUILDUP FACIES LITHOLOGY
STRATIGRAPHY
MANITOBA GROUP
ELK POINT GROUP
WINNIPEGOSIS FM
UPPER
LOWER
ASHERN
P.E.R.C.H.
WINNIPEGOSIS FORMATION
ELK POINT GROUP
ANGULAR CARBONATE CLASTS IN RED-GREEN SHALE MATRIX
DEFORMED SHALE AND LIMESTONE CLASTS IN GREEN CLAY MATRIX
THICKLY LAMINATED CARBONATE MUDSTONE WITH 1-20% FINE HEMOGENOUS MATTING
BIOTURBATED CRINOID-BRACHIOPOD MUDSTONES AND WACKESTONES VARIABLY DOLOMITIZED
GREY GREEN DOLOMITIC SHALE
DEFORMED SHALE AND LIMESTONE CLASTS IN GREEN CLAY MATRIX
LAMINATED DOLOMITE MUDSTONE FENESTRAL POROSITY AND PYRITE NODULES
DOLOMITE MUDSTONE WACKESTONE WITH SUBORDINATE (<10%) GRAIN SUPPORTED LITHOLOGIES AND (<10%) CORAL STROMATOPOROID FRAMESTONE - BINDSTONE
COMPLETELY DOLOMITIZED BIOTURBATED CRINOID-BRACHIOPOD MUDSTONE - WACKESTONE
STRUCTURELESS GREY GREEN DOLOMITIC SHALE
UPPER
LOWER
ASHERN
P.E.R.C.H.
WINNIPEGOSIS FORMATION
ELK POINT GROUP
P.E.R.C.H. PRAIRIE EVAPORITE RESIDUAL CLAY HORIZON

Fig. 5 Elk Point lithofacies.

diagenetic. The Ashern Shale is typically massive to crudely bedded and devoid of bioturbation. Norris et al (1982) noted the absence of body fossils. The upper contact is typically sharp and marked by a thin (5 to 50 cm) "microbreccia" containing angular clasts of grey-green shale in a green shale matrix.

INTERPRETATION OF THE ASHERN FORMATION

The age and depositional environment represented by the Ashern remains problematical due to the absence of diagnostic trace or body fossils and sedimentary structures. Sherwin (1962) suggested that the Ashern represents a marine or tidal-flat deposit formed during the early stage of the Elk Point transgression. McCabe (1967) observed that pronounced thickness variations of the Ashern Shale reflected Early Elk Point infilling of topography on the post-Silurian erosion surface. Whereas most workers conclude that the Ashern is part of the Elk Point transgressions, the author postulates that the "microbreccias" at the Ashern-Winnipegosis contact reflect post-Ashern, pre-Winnipegosis emergence. This would indicate that the Ashern represents an earlier, possibly non-marine, depositional event which perhaps was unrelated to the Elk Point transgression as suggested by Perrin (1982).

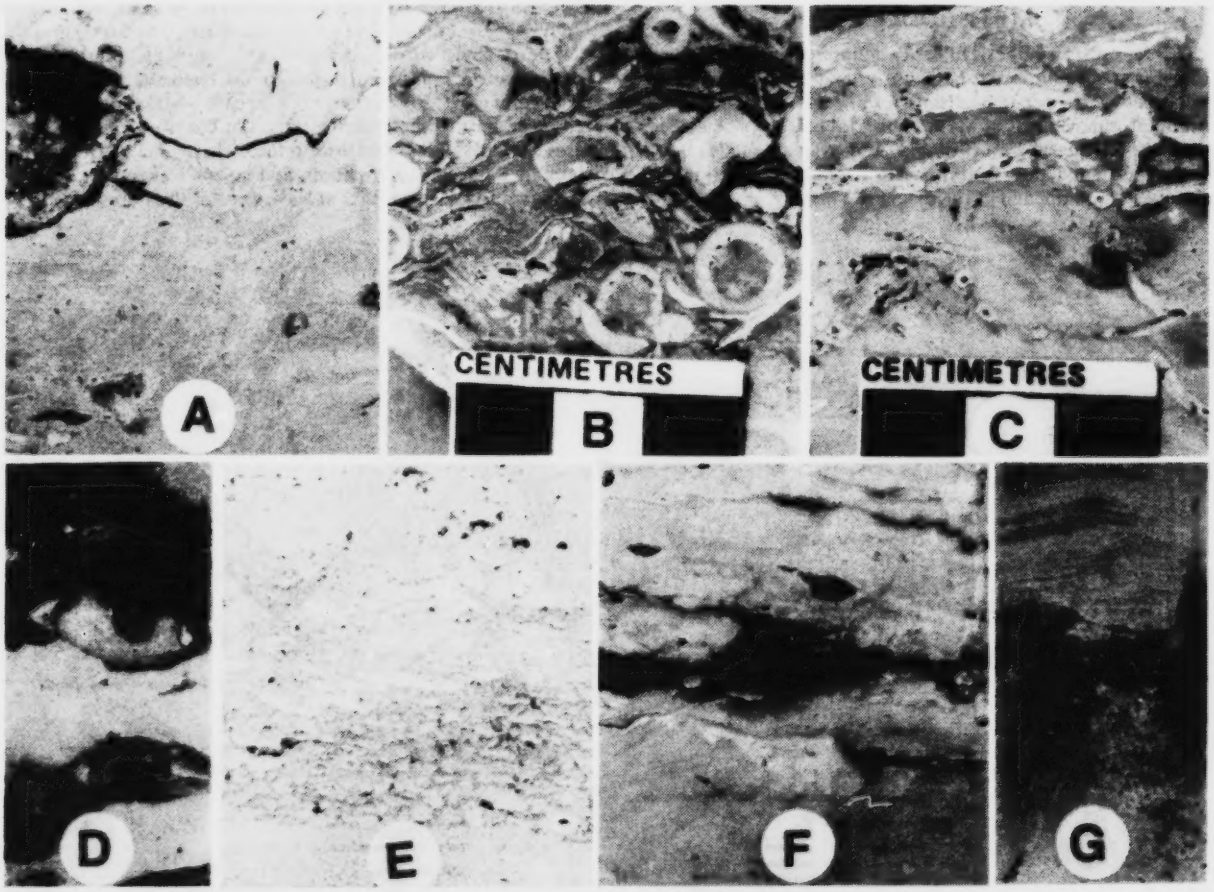


Fig. 6 Depositional textures and facies recognized in cores of the Upper Winnipegosis buildup (all photos same scale). A) Dolomitized wackestone-mudstone (Facies 3) showing massive, possibly bioturbated texture and rare crinoid fragments. Note large vug (arrow) filled with sparry dolomite and lined with bitumen? 3-29-35-26W1, 802' (244 m) depth, Swan River Area. B) Dolomitized crinoid-brachiopod mudstone (Facies 6). 15-32-36-26W1, 835' (254 m) depth, Swan River Area. C) *Amphipora* floatstone, completely dolomitized with poor moldic porosity 15-32-36-26W1,766' (233 m) depth, Swan River Area D) Partially dolomitized lime mudstone-wackestone (Facies 2). Note pristine preservation of crinoids and brachiopods in dark (limestone) domains and structureless dolomitic burrows devoid of fossils. Note also enigmatic coarse (to 1.5 cm) "eyes" (arrow) filled with sparry dolomite. M-1-72, 100' (31 m) depth, Narrows Area, Lower Winnipegosis member. E) Dolomitized intraclast conglomerate overlying thin oolitic grainstone. This was only observed in one core in Facies 6 dolomite mudstone and is included in that facies. 15-32-36-26W1, 865' (264 m) depth, Swan River Area. F) Algal dolomite mudstone with possible fenestral porosity (Facies 6). 15-32-36-26W1, 687' (209 m) depth, Swan River Area. G) Tabular stromatoporoid and *Favosites*? coral fragments in dolomite mudstone matrix (Facies 5). M-5-69, 100' (33.5 m) depth, Narrows Area.

LOWER WINNIPEGOSIS MEMBER

FACIES 2: CRINOID-BRACHIOPOD WACKESTONES AND MUDSTONES

The Lower Winnipegosis is a 7 to 18 m thick bioclastic and mud-supported carbonate which blankets the study area. In the M-1-72 Narrows well in the southern part of the study area, it consists of a tan to dark-brown crinoid-brachiopod lime mudstone-wackestone (Fig. 6D). Norris et al (1982) have differentiated this non-dolomitized unit as the Elm Point Member. This author considers it to be a facies variation of the Lower Winnipegosis without formal stratigraphic status. The tan-coloured mottling outlines sites of incipient dolomitization which appear to follow burrow forms. The dark-brown domains contain abundant disarticulated crinoid-brachiopod fragments in a bioturbated mud matrix in which the trace fossils *Paleophycus* and *Thalassinoides* were recognized. Coarse eyes of sparry dolomite up to 3 cm in diameter occur locally within the tan-coloured domains, apparently infilling solution voids (Fig. 6D). The limestone facies is also present in the Mafeking area (e.g. in M-2-73, M-7-78 cores).

Throughout the rest of the study area, the Lower Winnipegosis is a tan- to buff-coloured dolomite containing relict crinoid fragments in a finely crystalline dolomite matrix (Fig. 6A).

The thickness of the Lower Winnipegosis is nearly uniform (Fig. 4) although there is some evidence of increase below the major buildups (e.g. at 15-32-36-26W1). There is no evidence of deepening- or shallowing-upward trends, nor of exposure or hardground at the upper contact. The composition of the unit (limestone versus dolomite) and the presence or absence of carbonate buildups appear to be genetically and spatially unrelated (Fig. 4), although Norris et al (1982) have suggested that dolomitization in the Lower Winnipegosis is enhanced below or close to the buildups.

INTERPRETATION OF THE LOWER WINNIPEGOSIS

The abundance of crinoid and brachiopod fragments in a mud-supported matrix and the predominance of bioturbation features over wave-current structures are indicative of relatively deep subtidal conditions. This deposit apparently acted as a platform for subsequent buildups. The absence of internal cyclicity of shoaling or deepening-upward trends suggests that depth and energy conditions remained constant. It is difficult to estimate water depths for this facies. Modern brachiopod and crinoid banks have been found at depths of up to 700 m (Neumann et al, 1977). Although no depth-diagnostic criteria are present within the unit, the water depth probably did not exceed a few tens of metres during deposition.

The limestone and dolomite varieties were probably deposited under similar depositional conditions and their difference reflects different diagenetic processes.

UPPER WINNIPEGOSIS MEMBER

The transition to the Upper Winnipegosis is marked discrete "carbonate buildups" rising from the Lower Winnipegosis and by thinly laminated kerogenous carbonate mudstones lying between the buildups. The term "buildup" describes a lithologically distinctive mass of carbonate sediment which is typically thicker than, and probably stood higher than, surrounding carbonate sediment at the time of deposition (Heckel, 1972).

CARBONATE BUILDUPS

Dolomitized, mud-dominated carbonate buildups up to 60 m in height occur throughout the study area. The basal zone is typically a 2 to 5 m thick kerogenous carbonate mudstone which records nearly basin-wide euxinic sedimentation. In the central part of the major buildups (e.g. at M-6-76), this bed is absent. It appears to rise over a slightly thickened Lower Winnipegosis below the buildups and thereby suggests that several metres of topographic relief may have existed on the sea floor. The topographic highs may have served as sites for reef growth.

Although extensive dolomitization in the Upper Winnipegosis has obscured many depositional textures, four facies are recognized within the buildups.

FACIES 3: CRINOID-CORAL-AMPHIPORA (DOLOMITE) WACKESTONE-MUDSTONE

This facies forms most of the Upper Winnipegosis and consists of dolomitized tan to light-brown mudstones and wackestones. It is lithologically similar to Facies 2 except for local concentrations of solitary corals and *Amphipora* fragments. The proportion of bioclastic components varies dramatically over very short core intervals, and ubiquitous bioturbation has destroyed all physical sedimentary structures. Stromatactis, found in many Paleozoic mud mounds (Bathurst 1982), is notably absent.

FACIES 4: CRINOID-CORAL-AMPHIPORA (DOLOMITE) GRAINSTONE-PACKSTONE

This facies typically forms less than ten per cent of an Upper Winnipegosis buildup and is found in the middle and upper parts. It is generally tightly cemented by isopachous crusts of calcite and dolomite which occlude most or all of the interparticle voids. In thin sections, these crusts exhibit radiaxial extinction patterns similar to those interpreted by Kendall and Tucker (1973) as early marine cements.

FACIES 5: STROMATOPOROID CORAL-CRINOID FLOATSTONE-RUDSTONE

This facies forms less than one per cent of the Upper Winnipegosis buildups and consists of large clasts of corals, tabular and branching stromatoporoids, crinoids and brachiopods in a dolomitized mud matrix (Fig. 6B, C). No unequivocal framestone textures were recognized. This facies is best developed in the basal part of the Upper Winnipegosis in the M-5-69 well where it is a partially altered, porous, coarsely crystalline dolomite (Fig. 4).

FACIES 6: ALGAL-LAMINATED DOLOMITE MUDSTONE WITH RARE INTRACLAST CONGLOMERATE AND PISOLITE INTERBEDS

The upper parts of two Upper Winnipegosis buildups (M-6-76 and 15-32-36-26W1) comprise crudely laminated dolomite mudstone exhibiting algal lamination with associated fenestral porosity (Fig. 6F), minor intraclast breccia units (Fig. 6E), monolithic dolomite mudstone breccias (Fig. 9C) and laminated crusts interpreted as caliche (Fig. 7G). Locally, pisolites (Fig. 7H) are present. In the 15-32-36-26W1 core, algal mudstone dominates the uppermost 15 m and includes molds of large gastropods and pelecypods.

FACIES 7: CALCITE ALTERATION-ZONE

In the Mafeking area, a distinctive, yellow-grey, coarsely crystalline limestone (Fig. 7F) occurs at the top of the Winnipegosis in both buildup (S-5-75) and basin (M-2-73) cores (Fig. 4). The calcite is a replacement of primary depositonal textures and is defined as a calcite alteration-zone.

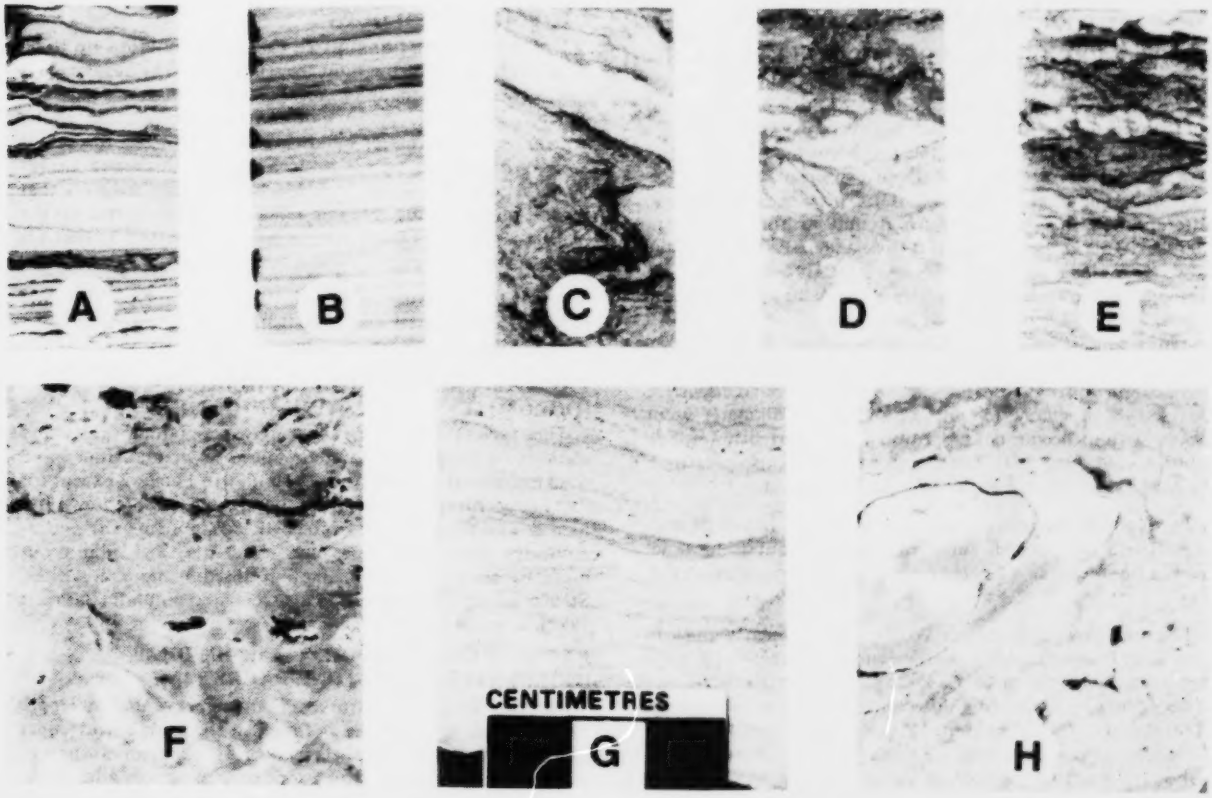


Fig. 7 Core photographs of Upper Winnipegosis basinal laminites (A-E) and diagenetic textures observed near the top of the Winnipegosis (F-H) (all photos same scale). A) Thinly laminated and kerogenous carbonate mudstone (Facies 9). 47-76-14, 290' (117 m) depth, Mafeking Area. B) Thinly laminated dolomite mudstone without kerogenous laminae (Facies 9). M-16-81, 290' (117 m) depth, Winnipegosis Area. C) Kerogenous dolomite mudstone with possible slump structures. M-5-76, 224' (68 m) depth, Winnipegosis Area. D) Collapse breccia containing clasts of kerogenous laminated dolomite mudstone. This indicates that some evaporites (now removed) were deposited prior to the close of Upper Winnipegosis euxinic basin sedimentation. 47-76-14, 238' (72.5 m) depth, Mafeking Area. E) Laminated kerogenous carbonate mudstone with excellent enterolithic structures, indicative of hypersaline and euxinic bottom waters between the buildups at the close of Upper Winnipegosis sedimentation. 15-32-36-26W1, 2 m below top of Winnipegosis, 639' (195 m) depth, Swan River Area. F) Coarsely crystalline calcite alteration zone with excellent vuggy porosity. 5-32-36-76W1, 639' (195 m) depth, Swan River Area. G) Laminated dolomite mudstone with possible caliche structures (Facies 6). 15-32-36-26W1, 3 m below top Winnipegosis, 635' (194 m) depth, Swan River Area. H) Coarse pisolites and possible oncolite in dolomite mudstone. 15-32-36-26W1, 7 m below top of Winnipegosis, 658' (200 m) depth, Swan River Area.

This facies reaches an observed maximum thickness of 8 m in the S-5-75 core, where it grades downwards into coarsely crystalline dolomite of Facies 5.

FACIES 8: SUCROSIC MICROCRYSTALLINE DOLOMITE

In the Narrows area of the central Interlake region (Fig. 3), the upper part of the Upper Winnipegosis is a finely crystalline (sucrosic) dolomite devoid of relict sedimentary textures. Recrystallization is most pervasive at the present surface, and the unit appears to grade downward into bioturbated mudstone-wackestone (Facies 3) which retains most of the original depositional textures.

BASIN DOMAINS

Between the carbonate buildups the Upper Winnipegosis consists of a 1 to 15 m thick kerogenous carbonate mudstone called the laminite facies.

FACIES 9: LAMINITE FACIES

The carbonate mudstones are thinly laminated (0.1 to 2 mm) and exhibit variable proportions of very fine kerogenous partings (Fig. 7A). Individual laminae typically pinch and swell across the width of the narrow (2 cm) cores and are notably devoid of ripple lamination, grading or scouring. Bioturbation is absent. Many kerogenous laminae are enhanced by styolitization (Fig. 7A). Soft-sediment deformation structures (Fig. 7C), microfolded (enterolithic) calcite laminae (Fig. 7E) probably pseudomorphous after displacive gypsum, and thin breccia layers containing angular clasts of kerogenous mudstones (Fig. 7D) occur near the top of the Winnipegosis. Small-scale cyclicity was recognized in several cores. In the Upper Winnipegosis of the 47-76-14 core, three distinct, metre-thick, "cleaning-upward" cycles are present. In these cycles, highly kerogenous, thinly laminated dolomite mudstones grade into poorly kerogenous, weakly laminated dolomited mudstones near the top. In other wells (e.g. M-16-81), no cyclicity was recognized. In several cores (e.g. from M-16-81), sharp-based beds of bioclastic mudstone (Facies 3) up to several centimetres thick are interbedded with kerogenous mudstones. No evidence of emergence or exposure was seen.

In the southern and central areas, the basin sequence yields to a laminite of carbonate mudstone. However, in the northern part of the study area around Mafeking, the laminite mudstones are interbedded with several metres of bioturbated bioclastic mudstone.

INTERPRETATION OF THE UPPER WINNIPEGOSIS

The Winnipegosis buildups contain an open-marine crinoid-coral-stromatoporoid fossil assemblage which suggests that

the Elk Point Basin was of normal marine salinity. The dominance of mud-supported textures and paucity of framework and grain-supported lithologies indicate low-energy conditions. The absence of true framework textures and stromatactis is enigmatic and indicates that the buildups were neither the true "organic reefs" of Heckel (1972) nor the classic Waulsortian mud mounds of Bathhurst (1982). Algal mudstones, intraclast breccias and pisolites at the top of the major buildups (e.g., at 15-32-36-26W1) suggest near-emergent shoaling conditions prior to the close of sedimentation.

The laminite facies represents deposition in a deep basin devoid of significant clastic input. The absence of bioturbation and the preservation of kerogenous laminae indicate that the deeper parts of the basin were euxinic. Two lines of evidence which suggest that bottom waters were also hypersaline (at least during the late stages of Upper Winnipegosis deposition) are:

1) enterolithic calcite laminae which have pseudomorphically replaced displacive gypsum layers (Fig. 7E), and
2) collapse breccias containing clasts of laminites (Fig. 7D); this relationship indicates that evaporites originally underlay the uppermost laminite beds and that their removal led to fracturing and collapse of the overlying laminite.

Davies and Ludlam (1973) documented similar structures and textures in kerogenous laminites of the Winnipegosis in the Williston Basin and demonstrated that individual laminae could be traced for up to 25 km. This high degree of consistency does not appear to be true of the laminite facies of this report, although more detailed studies are needed to evaluate this. However, in all other aspects, they are virtually identical.

The transition from Winnipegosis to Prairie Evaporite sedimentation appears to have been gradational, at least in the basin areas, because the uppermost laminite beds exhibit evidence of hypersalinity and euxinic bottom conditions. Evidence is lacking of an emergent stromatolitic horizon at the top of the basinal laminite facies such as Perrin (1982) has described from North Dakota.

The carbonate buildups are apparently equivalent to the lower (nonevaporitic) part of the euxinic basin laminites. A drop in sea-level, either of eustatic or of evaporative origin, could have exposed the crest of the buildups and arrested their growth. Deposition of laminated carbonate mudstones between the reefs continued uninterrupted, even as bottom waters became euxinic and hypersaline in a transition to the increased restriction of the Prairie Evaporite basin.

PRAIRIE EVAPORITE RESIDUAL CLAY HORIZON

FACIES 10: SLURPY CLAYSTONE

This facies is seen at the contact of the Upper Winnipegosis carbonates and the collapse breccias of the Mafeking Member of the Dawson Bay Formation. It consists of a grey-green shale-claystone with abundant clasts and contorted laminae of grey microcrystalline limestone which exhibit a distinctive "slurpy" looking texture (Fig. 9B). Many of the clasts have vague smeared margins which grade into the adjacent clay matrix. Termed the "transition beds" by Norris et al (1982), this facies is here distinguished as a separate stratigraphic unit because of its striking difference from units above and below it. In most cases, the unit is less than 2 m thick.

INTERPRETATION OF RESIDUAL CLAY HORIZON

The collapse breccia is probably related to removal of the Prairie Evaporite and the green clay probably represents insoluble residue of the evaporite. The origin of the crystalline limestone clasts and contorted laminae (Fig. 9B) is obscure because the clasts appear to have developed contemporaneously with solution of the evaporite. It is noteworthy that green clay is always found above the Winnipegosis carbonate and never in even the top few centimetres of the underlying porous dolomite. This suggests that the fluids which dissolved the Prairie Evaporite were ascending rather than downward percolating. Galloway (1984) has noted that formation fluids are expelled from sediments by compaction during the depositional phase of basin evolution. Thus the present hydrologic regime is probably not responsible for removal of most of the Prairie Evaporites in the study area.

OUTCROP EXPOSURES OF WINNIPEGOSIS STRATA

Four outcrop and quarry exposures of the Winnipegosis Formation were examined during the study, and the location of three of them are shown in Fig. 1. The Lily Bay East quarry was not plotted as it is located approximately 50 km south-southeast of the southern limit of the map area. In general, the outcrops expose stratigraphic sections only a few metres long, and the absence of well defined markers hinders precise determination of the stratigraphic interval represented. The outcrops were not measured in detail but the following observations were made:

1) The Lower Winnipegosis was examined only in the Lily Bay East quarry (Fig. 8A). The partially dolomitized crinoid-brachiopod wackestone-mudstone is intensely bioturbated, and large branching *Thalassinoides* burrows are evident on the southern face of the quarry (Fig. 8A). This unit is similar to Facies 3. The depositional textures probably originated in a shallow subtidal setting.
2) The basal part of the Upper Winnipegosis is exposed in the Mason Island outcrop (H. R. McCabe, pers. comm.) and consists of well bedded crinoid rudstone-grainstone (Fig. 8B). The bedding dips at low angles (10 to 20°) in opposite directions on opposite sides of the island. This suggests that the shape of the island conforms to a crinoid bank with several metres of relief. An analogous facies was not recognized in the drill cores, so this appears to be a local feature. James (1984) has described similar bodies which form the initial "stabilization" stage of reef growth.
3) The Rock Island outcrops contain spectacular exposures of tan- to buff-coloured stromatoporoid-coral bindstone and framestone in the Middle-Upper Winnipegosis (Fig. 8C). Massive, tabular and encrusting stromatoporoids and subordinate colonial corals are featured although extensive leaching and dolomitization have obscured most of the primary depositional textures. This was the only unequivocal example of a true "organic reef" observed in any of the Winnipegosis outcrops or cores. It probably represents a high-energy subtidal environment.
4) The uppermost few metres of the Upper Winnipegosis member is exposed in the Salt Point West outcrop (H. R. McCabe, pers. comm.). Porous algal mudstones with a gastropod-pelecypod fauna exhibit excellent fenestral fabrics, possible algal laminations (Fig. 8D) and teepee structures (Fig. 9A). These observations are all consistent with shoaling conditions and the establishment of restricted intertidal environment on the crest of the buildups.

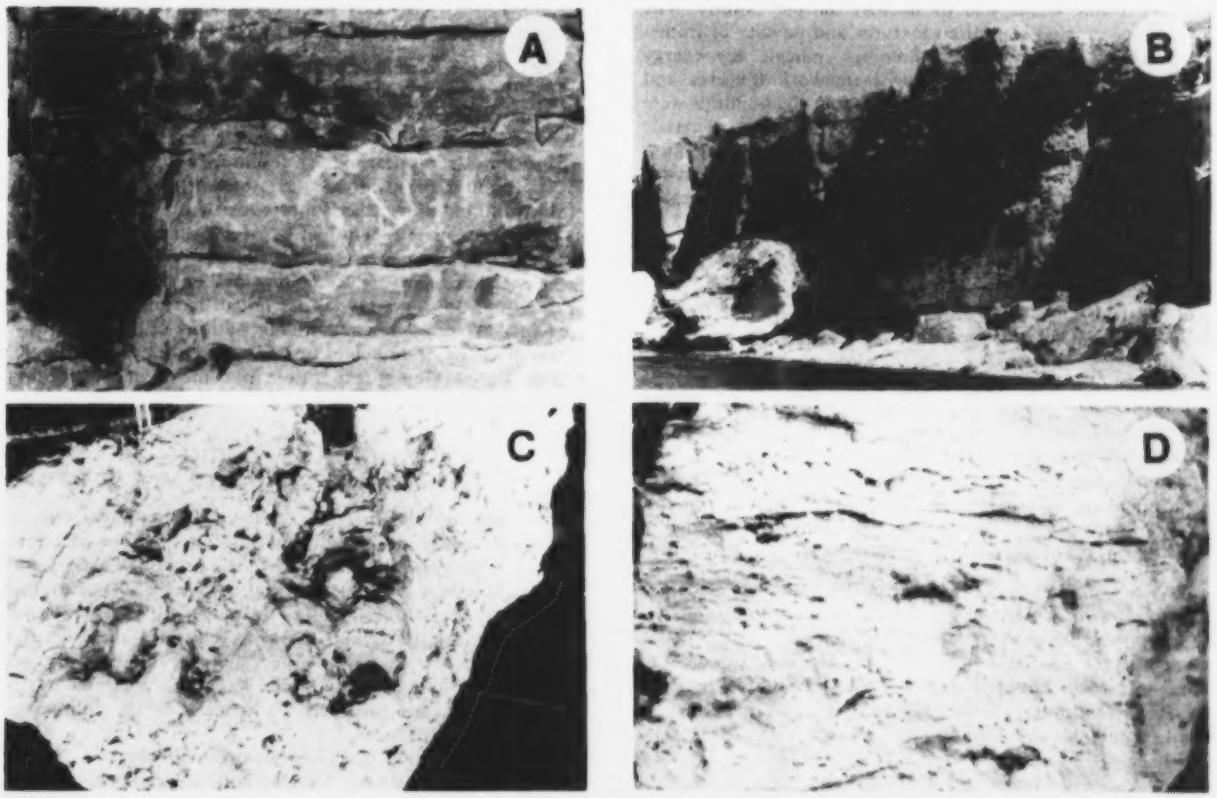


Fig. 8 Outcrop photos, Winnipegosis Formation, Mafeking - Narrows Area. A) Partially dolomotized mudstone-wackestone (Facies 2), lower Winnipegosis (Elm Point Member), Lily Bay East Quarry (hammer for scale). Note large branching *Thalassinoides* burrows (arrow). B) Bedded crinoid and rudstone-grainstone (Facies 4, 5), Mason Island outcrop (seagull for scale). Note 10 to 20° dip to the bedding (regional dip is less than 1°). Bedding dips in opposite direction 0.5 km away on other side of the island, suggesting that this island knoll represents a crinoid bank which exhibited topographic relief at a time of deposition. C) Dolomotized stromatoporoid bindstone, Rock Island outcrop (hammer for scale). Note encrusting stromatoporoids draping coral rubble. D) Dolomotized algal mudstone (Facies 6) exhibiting fenestral and vuggy porosity, Salt Point West outcrop (photo width approximately 1 metre). This grades laterally into the teepee structure shown in Figure 9A.

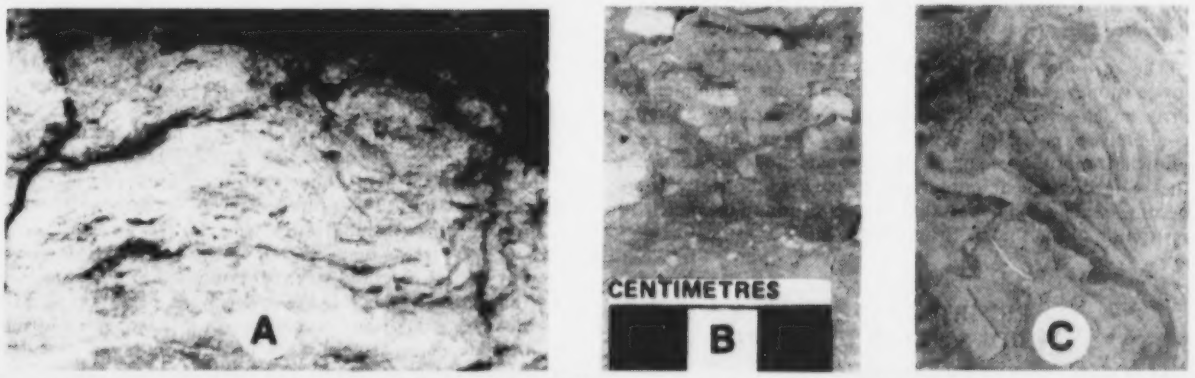


Fig. 9 A) Teepee structure in laminated dolomite mudstone (Facies 6) near top of Upper Winnipegosis, Salt Point West outcrop (photo approximately 1 m in width). B) Slurpy claystone breccia (Facies 10) in the Prairie Evaporite Residual Clay Horizon, consisting of amorphous clasts and laminations of fine crystalline limestone in a grey-green argillaceous matrix. 3-29-36-25 W1, 770'(235 m) depth, Swan River Area. C) Dolomitized mudstone breccia containing rounded and angular mudstone clasts in a dolomite mudstone matrix. This facies was only observed in a few cores within the laminated dolomite mudstone (Facies 6) interval near the top of the upper Winnipegosis buildups and was included in that facies. 15-32-36-26W1, 640', (196 m), Swan River Area (same scale as B).

DIAGENETIC HISTORY OF THE WINNIPEGOSIS BUILDUPS

Diagenesis of the Winnipegosis Formation was not investigated in detail but the following observations are submitted.

1) Locally, within "grainy" parts of the Upper Winnipegosis buildups (e.g., M-6-76), an isopachous sparry carbonate cement occludes most of the interparticle spaces. This appears superficially similar to the radiaxial acicular crusts described by Kendall and Tucker (1973). However, extensive micritization which apparently accompanied the dolomitization has obliterated fine petrographic details. These crusts are interpreted as early cements precipitated within the pores of the buildups by marine waters.
2) All of the Upper Winnipegosis buildups and most of the Lower Winnipegosis have been intensely dolomitized. This

dolomitization appears to have accompanied micritization of fossil fragments, matrix, and early cements. In several cases, hand samples identified as mudstones were recognized in thin section to contain grain-supported textures. This dolomitization could have been initiated by two diagenetic processes.

3) **(a) Seepage Refluxion.** Collapse breccias on the Winnipegosis carbonate are presumably related to removal of a thick evaporite which had blanketed the study area. Magnesium-rich brines which deposited the evaporites may have percolated into the underlying carbonate and dolomitized it by seepage refluxion as described by Adams and Rhodes (1960).

(b) Mixing Zone (Dorsg) Dolomitization. Algal mudstones at the top of the buildups suggest either partial or complete emergence during a drop in sea level. Meteoric fluids, analogous to those described by Badiozamani (1973), Land (1973), and Folk and Land (1975), could have initiated dolomitization in a zone of mixing with saline pore waters. Wardlaw and Reinson (1973) and Perrin (1982) have suggested that this process might account for dolomitized Winnipegosis reefs in other parts of the basin. Sears and Lucia (1980) described a similar relationship in the Silurian reefs of the Michigan Basin and used mass balance equations to demonstrate that seepage reflux would be more efficient and rapid at promoting dolomitization than a mixing-zone process.

4) The final stage of diagenesis is calcite alteration at the top of the Winnipegosis strata in the Mafeking area. Why this facies is restricted to this locality is unclear. The zone is texturally similar to products of dedolomitization which occur contemporaneously with evaporite dissolution (Blatt et al, 1980, p. 531). However no rhombic crystals (possibly pseudomorphous after dolomite) were recognized. Likewise, the origin of finely crystalline dolomite textures in the Narrows area is unknown, although the pervasive recrystallization at the present exposure surface indicates these textures to be late diagenetic.

AN INTEGRATED CORE-OUTCROP MODEL FOR WINNIPEGOSIS CARBONATES IN MANITOBA

The depositional and diagenetic history of the Winnipegosis Formation can be summarized in six stages (Fig. 10).

1) Deposition of Lower Winnipegosis crinoid-brachiopod mudstones and wackestones in water depths of a few tens of metres. This formed a blanket-like deposit which may have had a low topographic relief prior to the end of sedimentation (Fig. 10A).
2) Initial basin restriction created euxinic conditions over most of the sea floor. Muddy crinoid banks, possibly similar to those exposed at Mason Island, projected above the oxygen minimum, thus did not accumulate kerogenous sediment, and may have served as bases for the Winnipegosis buildups (Fig. 10B).
3) Continued differentiation of the sea floor into buildups and basin resulted in mud-dominated carbonate banks building vertically and prograding laterally (in the Mafeking area) in response to rising sea level (Fig. 10C). Organic frameworks comprise only a small part of the buildups. It is not clear whether or not the organic material represents a core flanked by subtidal mudstone or a rigid rim enveloping lagoonal mudstones. The absence of stromatactis suggests these buildups are not Waulsortian-type mud mounds (Fig. 10C). Deposition of kerogenous carbonate mudstones continued in euxinic waters between the buildups.

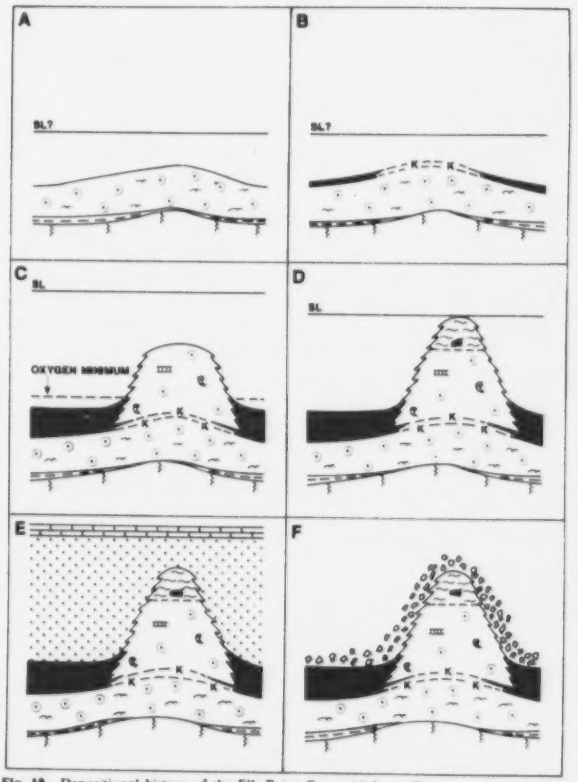


Fig. 10 Depositional history of the Elk Point Group (Ashern, Winnipegosis, and Prairie Evaporite Formations) in west-central Manitoba.

4) Shoaling and emergence of the buildups resulted in deposition of a capping laminated mudstone more than 15 m thick. This mudstone exhibits excellent fenestral porosity and is associated with pisolites, intraclast breccias, and teepee structures. Karst-type breccias in some cores suggest complete emergence which may have initiated mixing-zone dolomitization of the buildups and adjacent platform sediments (Fig. 10D). Increased restriction and elevated salinities might have permitted deposition of the enterolithic gypsum-laminated mudstones between the buildups at this time.
5) Deepening and/or increased restriction (Fig. 10E) led to deposition of an undetermined thickness of evaporites across the Elk Point Basin. Dolomitization of the Winnipegosis carbonates could have occurred by seepage refluxion at this time.
6) Post-Dawson Bay dissolution across the outcrop belt led to removal of the Prairie Evaporite (Fig. 10F). The timing is poorly constrained, but McCabe (1967) has indicated that episodic solution occurred throughout the upper Paleozoic and Mesozoic. In the Mafeking area, possible dedolomitization which accompanied dissolution of the evaporites created the porous, vuggy, crystalline calcite alteration zone at the top of the Winnipegosis Formation.

IMPLICATIONS FOR EXPLORATION IN THE NORTHERN WILLISTON BASIN

The extent to which diagenetic and depositional models developed in the outcrop is applicable to the equivalent strata in the deeper "oil prone" part of the basin cannot be evaluated without much additional study. However, the following points should be considered by explorationists working in the northern Williston Basin.

1) True organic reefs dominated by colonial corals and tabular and encrusting stromatoporoids are present in the Manitoba outcrop belt. These buildups have steep margins. Organic framework apparently forms only a small part of the buildups and in fact was observed in only one outcrop (Rock Island). Whether the organic framework formed a resistant rim around a muddy lagoon or represents a rigid "core" flanked by carbonate mudstone and wackestones is not clear.
2) There is no interdigitation of buildup and basin facies and most buildups appear to have resulted from one transgression-vertical accretion-exposure cycle. The exception is the core (M-5-69), wherein a possible exposure surface is present in the middle of the Upper Winnipegosis. The Winnipegosis buildups thus differ from Upper Devonian reefs of the Alberta Basin which are multistage (e.g. Fischbuch, 1968).
3) Porosity is enhanced in, but not restricted to, the organic framework. Some of the "grainy" subtidal lithologies are tightly cemented by an isopachous marine cement. The good fenestral and vuggy porosity which was observed in the uppermost 5 to 10 m of the buildups was presumably formed during emergence. The best porosity in the study area is found in the crystalline calcite alteration zone at Mafeking. This zone may have been created by late dedolomitizing fluids entering from fractures along the Churchill-Superior tectonic boundary. Similar north-striking lineaments elsewhere (e.g. the Nesson-Tabernor Break) could have excellent reservoir prospects.

ACKNOWLEDGEMENTS

The writer is grateful to H. R. McCabe of the Manitoba Mines Branch for leading an excellent field trip to the outcrops. Many of the ideas presented in this paper are a direct outgrowth of conversations in that trip. Harvey Young's suggestions and comments improved the final manuscript. Karen Taylor is thanked for typing the final draft, and Norma Bristol's drafting skills greatly improved the diagrams.

REFERENCES CITED

Adam, J. E., and Rhodes, M. L., 1960, Dolomitization by seepage refluxion. Am. Assoc. Petroleum Geologists Bull., v. 44, p. 1912-1920.

Badiozamani, K., 1973, The Dorag dolomitization model; application to the Middle Ordovician of Wisconsin. Jour. Sed. Petrology, v. 43, p. 965-984.

Baillie, A. D., 1951, Devonian Geology of Lake Manitoba-Winnipegosis area. Manitoba Mines Branch Publication # 49-2, 56 p.

Baillie, A. D., 1953, Devonian System of the Williston Basin area, Manitoba. Manitoba Mines Branch Publication #52-5, 28 p.

Bathurst, R. G. C., 1982, Genesis of *Stromatactis* cavities between submarine crusts in Paleozoic carbonate mud mounds. Jour. Geol. Soc. Lond., v. 129, p. 165-181.

Blatt, H., Middleton, G. V., and Murray, R., 1980, Origin of Sedimentary Rocks. Prentice Hall, New Jersey, 782 p.

Davies, G. R., and Ludlam, S. D., 1973, Origin of laminated and graded sediments, Middle Devonian of Western Canada. Geol. Soc. America Bull., v. 84, p. 3527-3546.

Fischbuch, N. R., 1968, Stratigraphy of the Devonian Swan Hills Formation of Central Alberta. Bull. Canadian Petroleum Geology, v. 16, p. 444-456.

Folk, R. F., and Land, L. S., 1975, Mg/Ca ratios and salinity: two controls over dolomite crystallinity. Am. Assoc. Petroleum Geologists Bull., v. 59, p. 60-68.

Fuzesy, L. M., 1975, Geology and hydrocarbon potential, Winnipegosis Formation of southeastern Saskatchewan. Saskatchewan Geological Survey, Summary of Investigations, p. 66-70.

Galloway, H. E., 1984, Hydrogeologic regimes of sandstone diagenesis. In: McDonald, R. A., and Surdam, R. C., eds., Clastic Diagenesis. Am. Assoc. Petroleum Geologists Mem. #37, p. 3-14.

Gendzwill, H., 1978, Winnipegosis mud mounds and Prairie Evaporite of Saskatchewan; a seismic study. Am. Assoc. Petroleum Geologists Bull., v. 62, p. 73-86.

Heckel, P. H., 1972, Carbonate buildups in the geologic record: a review. In: Laporte, L. F., ed., Reefs in Space and Time. Soc. Econ. Paleontologists Mineralogists Spec. Pub., v. 16, p. 90-154.

James, N., 1984, Reefs. In: Walker, R. G., ed., Facies Models. Geological Association of Canada, Reprint Series, 2nd Edition, p. 229-244.

Jones, J. L., 1965, The Middle Devonian Winnipegosis Formation of Saskatchewan. Saskatchewan Department Mineral Resources Report # 98.

Kendall, A. C., and Tucker, M. E., 1973, Radiaxial fibrous calcite; a replacement after acicular carbonate. Sedimentology, v. 20, p. 365-388.

Land, L. S., 1973, Holocene meteoric dolomitization of Pleistocene limestones, Jamaica. Sedimentology, v. 20, p. 411-422.

McCabe, H. R., 1967, Tectonic framework of Paleozoic Formations in Manitoba. Can. Instit. Min. Metallurgy Bull., v. 54, p. 765-774.

Norris, A. N., Uyeno, T. T., and McCabe, H. R., 1982, Devonian Rocks of the Lake Winnipegosis Lake Manitoba Outcrop Belt, Manitoba. Geological Surv. Canada Mem. 392, 280 p.

Neumann, A. C., Kofoed, J. W., and Keller, G. H., 1977, Lithoherms in the Straits of Florida. Geology, v. 5, p. 4-10.

Perrin, N., 1982, Environments of deposition and diagenesis of the Winnipegosis Formation, Williston Basin,North Dakota. In: Christopher, J., and Kaldi, J., eds., 4th Williston Basin Symposium. Saskatchewan Geological Society Spec. Pub. #6, p. 51-66.

Sears, S. O., and Lucia, F.J., 1980, Dolomitization of northern Michigan Niagaran reefs by seepage refluxion and meteoric mixing. In: Zenger, D. H., and Dunham, J. B., eds., Concepts and Models of Dolomitization. Soc. Econ. Paleontologists Mineralogists Spec. Pub. # 28, p. 215-246.

Tyrell, J. B., 1892, Three deep wells in Manitoba. Royal Society of Canada Transactions, v. 9, p. 91-104.

Wardlaw, N. C., and Reinson, G. E., 1971, Carbonate and evaporite deposition and diagenesis, Middle Devonian Winnipegosis and Prairie Evaporite Formation, south-central Saskatchewan. Am. Assoc. Petroleum Geologist Bull., v. 55, p. 1759-1786.

DISTINGUISHING BETWEEN DEPOSITIONAL AND DISSOLUTION THINNING: DEVONIAN PRAIRIE FORMATION, WILLISTON BASIN, NORTH AMERICA

CHRIS A. OGLESBY

Department of Geology and Geological Engineering
Colorado School of Mines
Golden, Colorado 80401

ABSTRACT

Abrupt lateral thickness variations within the Prairie Formation are common and caused by two disparate but distinguishable processes; differential accumulation of salt during deposition and differential removal of salt by dissolution. Direct differentiating evidence, such as the presence of collapse breccias is preferred; however it is not often observed because the Prairie/ Winnipegosis interval is seldom cored. Therefore indirect methods, utilizing well logs, provide the primary method for interpreting occurrences of the two processes. The results of this study indicate that the two processes can be distinguished using Prairie intraformational correlations.

There are several regionally correlative shoaling upward sequences within the Prairie Formation. The lowermost sequence begins with the transition from the Winnipegosis Formation laminated carbonates to the basin-centered Ratner anhydrite, followed by halite and culminating in the Esterhazy potash beds. Two overlying sequences also display shallowing upward trends; however, these sequences begin with halite and culminate in the Belle Plaine and Patience Lake (Mountrail) potash Members respectively. A fourth sequence is indicated by several additional feet of halite capping the Patience Lake in some parts of the basin. Complete desiccation and subsequent erosion or dissolution prior to burial may have removed the upper portion of this sequence.

Cross-sections show a regional, gradual decrease in thickness in the lower Prairie away from the basin depocenter. This is most simply explained by decreasing the subsidence rates away from the basin depocenter and by depositional onlap of the Prairie toward the basin margins. This depositional onlap pattern occurs along the basin's southern margin. By correlating the four sequences within the Prairie, some local thickness variations are shown to originate by depositional onlap onto Winnipegosis reefs. In this case, there is a progressive increase in areal extent of the formation from the base to the top. In other instances, such as along the western and eastern basin margins, the basal parts of the formation are preserved but the upper parts are progressively restricted. This pattern is explained by progressive dissolution of Prairie evaporites from the top downward.

INTRODUCTION

Salt measures within the Williston Basin are numerous, ranging in age from Silurian to Jurassic. The thickest and most laterally extensive evaporites are those of the Middle Devonian (Givetian) Prairie Formation. The Prairie evaporites consist predominantly of halite with lesser amounts of anhydrite and potash. Anomalous areas of thinning within the Prairie Formation have been documented in both the Canadian and U.S.A. portions of the basin. The thinning can be attributed to two processes; differential accumulation of salt during deposition and differential removal of salt by dissolution. An understanding of the two processes and their resulting effects are important to distinguish between them. Recognition and prediction of dissolution and depositional "thin" areas are important to mining and petroleum exploration and development.

The study area includes the Montana and North Dakota portion of the Williston Basin (Fig. 1) within the present-day Prairie Formation subcrop. Several regional cross-sections of the Elk Point Group (Fig. 2) were constructed to ascertain the processes responsible for the thickness changes within the Prairie Formation across the basin. These cross-sections were supplemented by several computer-generated regional isopach maps of the Prairie and Winnipegosis intervals. Areas of anomalous thinning, such as the Roosevelt County, Montana salt void, the eastern basin Winnipegosis pinnacle reef area and the current salt edge were studied in detail. In all instances, three working hypotheses, depositional versus dissolution processes-oriented were tested.

Using intraformational sequences within the Prairie as correlation units, emphasis was placed upon recognizing thickness changes within the Prairie Formation. The results of this study indicate that dissolution and depositional thinning of the Prairie Formation can be distinguished by utilizing Prairie intraformational correlations.

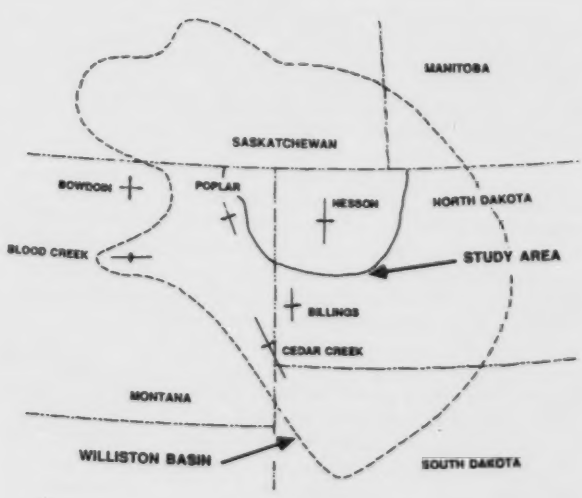


Fig. 1 Study Area - Subcrop of Prairie Formation within the Williston Basin.

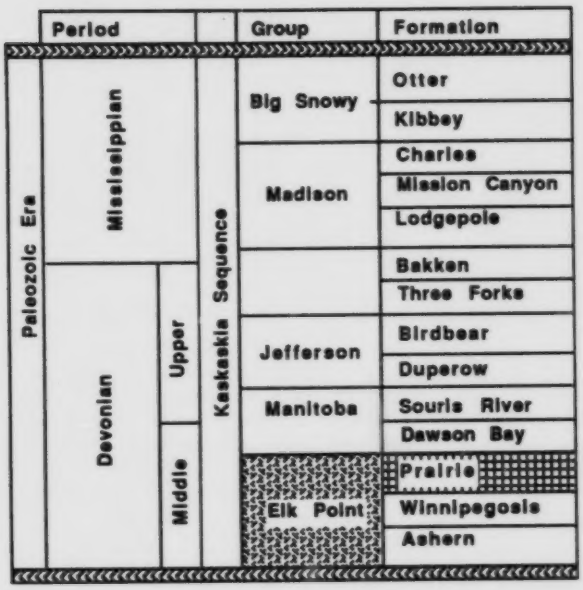


Fig. 2 Stratigraphic column for the Kaskaskia Sequence in the study area. The primary interval of the study was the Prairie Formation of the Elk Point Group.

PRAIRIE FORMATION DEPOSITIONAL SEQUENCES

A depositional sequence has been defined as "a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities" (Mitchum et al, 1977). Within the Prairie Formation there are several regionally correlative shoaling (or shallowing) upward asymmetric sequences. Although they are incomplete, these sequences are similar to the Paradox Basin cycles described by Peterson and Hite (1969) and to a hypothetical deep-basin sequence described by Kendall (1984). Peterson and Hite noted that the potash-capping sequences were asymmetrical and had a very sharp upper contact with the overlying lithology which manifested itself as a disconformity formed by dissolution during deposition of the overlying (lower salinity) facies. Kendall's deep basin sequence begins with laminated carbonates within the starved basin and then progresses to laminated gypsum, laminated halite, chevron halite and finally ends with deposition of potash salts.

Similar successions are present in the Prairie Formation. The lowermost sequence begins with the transition from the Winnipegosis Formation laminated carbonates (laminites) to the basin-centered Ratner anhydrite (which changes vertically from laminated to enterolithic), followed by a thick sequence of halite and thinly interbedded anhydrite (jahresringe) and culminating in the Esterhazy potash beds. Two overlying sequences, although incomplete, also display shoaling upwards trends. These incomplete sequences begin with halite and culminate in deposition of the Belle Plaine and Patience Lake (Mountrail) potash members respectively. A fourth incomplete sequence is suggested by the presence of several additional feet of halite overlying the Patience Lake Member in some parts of the basin (Fig. 3). Complete desiccation and subsequent erosion prior to burial may have removed the upper portion of this sequence. This unconformity may be manifested by the presence of the Second Red Bed which conformably overlies the Prairie (Williams, 1984).

Intra-formational correlations within the Prairie were accomplished using gamma-ray and sonic logs (Fig. 4). High gamma-ray values occur within the cycle-capping potash beds due to the high amount of radioactive potassium (K^{40}) present (Timko, 1964). Similarily, the extreme solubility of the evaporites in contrast to the adjacent carbonates commonly resulted in deep washouts which are manifested as very slow travel times or high sonic porosity values. Using these correlative units as datums, thinning within the Prairie both above and below the potash units was evaluated.

DEPOSITIONAL THINNING (ONLAP)

Considerable controversy remains concerning the water depth during deposition of the Prairie Formation. Evaporite deposition within either a shallow salt pan or deep basin model results from basin restriction and high evaporation rates. Unlike clastic and carbonate settings, the depositonal mode is entirely aggradational (resulting from crystal nuclei formation and settling, followed by incipient crystal growth) and not progradational (Figs. 5 and 6). Therefore, the accommodation potential is primarily related to the amount of basin subsidence in the salt pan model and to a combination of subsidence and water depth in the deep basin model, and not to major changes in depositional environments. Aggradational deposition of evaporites results in an onlap geometry as the basin becomes progressively filled.

Regional cross-sections from the basin center to the basin flanks display a relatively constant amount of thinning that is most easily explained by decreasing subsidence rates towards the basin margins. Most of this thinning occurs within the lower Prairie Formation below the Esterhazy potash member; however, a portion of the thinning within the upper Prairie also can be attributed to decreasing subsidence rates. Depositional onlap of the Prairie towards the basin margins through time resulted in a thick basin-centered lower Prairie halite/anhydrite deposit which filled in the deep basinal portion of the Winnipegosis basin and then, once filled, onlapped onto the pre-existing Winnipegosis shelf. It was not until the central basin was filled, that the cyclic and probably shallower water halite/potash cycles were initiated.

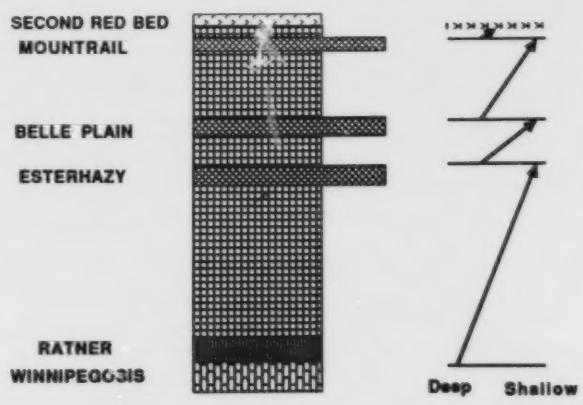


Fig. 3 Asymmetric shallowing upward sequences within the Prairie Formation.

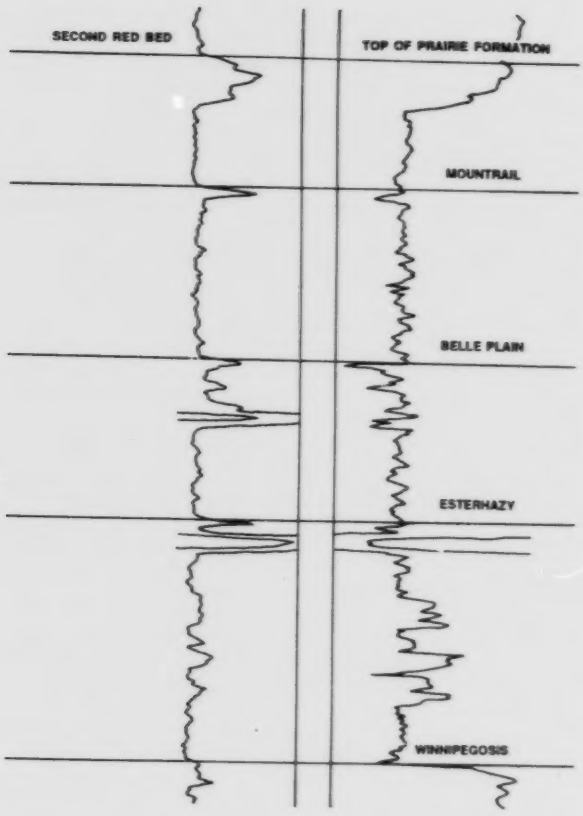


Fig. 4 Typical gamma-ray, sonic log through the Prairie formation. High gamma-ray and low sonic values correspond to the potash beds within the Prairie.

Onlap of Prairie evaporites onto the Winnipegosis reefs also seems to be the dominant process causing thinning over the eastern basin pinnacle reefs (Fig. 7). Although excellent Prairie correlation units above the reefs are seldom available, approximate correlations as well as the evidence that the combined Prairie/ Winnipegosis isopach thins very little over the reefs, suggests that depositional onlap accounts for most, but probably not all, of the Prairie Formation thinning.

DISSOLUTION THINNING

Three processes have been advanced to explain dissolution phenomena. While all utilize dynamic fluid movement, the driving forces and the mechanisms localizing dissolution differ. Some authors (Illing, 1959; Jodry, 1960) have suggested that the dissolution is caused by fluids driven out of the adjacent strata and into the porous and permeable reef during burial and compaction. This process requires an upward-directed water flux through the Winnipegosis, dissolving the overlying evaporites of the Prairie Formation. Davis (1972), in his study of upper Devonian reefs in Alberta, noted anomalous high velocity zones in the overlying section above the Leduc reefs. He attributed this to diagenetic changes caused by connate fluids flowing out of the surrounding Ireton shales and into the adjacent Leduc reefs during burial and compaction. These phenomena were found to be local in occurrence and restricted to the immediate reef vicinity.

Similar phenomena could be expected to occur near Winnipegosis reefs; however because the surrounding strata are evaporites rather than shales, lesser volumes of water should be available during basin dewatering and compaction. Two observations suggest that this process may have occurred on a minor scale (Fig 8): 1) the highly soluble potash beds rarely are present over the reefs, although the reefs were sufficiently buried at that time so they should not have been a topographic barrier; and 2) thinning at the scale of tens of feet over the reefs does not appear to be depositionally related.

Unlike the compaction and dewatering hypothesis, two other models have been advanced which require potentiometric flow as the driving mechanism. Simpson (1978) suggested that major dissolution periods corresponded with the timing of major unconformities of Sloss (1963). He noted a coincidence between the periods of anomalous thickening overlying salt dissolution areas (voids) and the major periods of emergence or oscillatory eustatic modes identified by Sloss (1963, 1974).

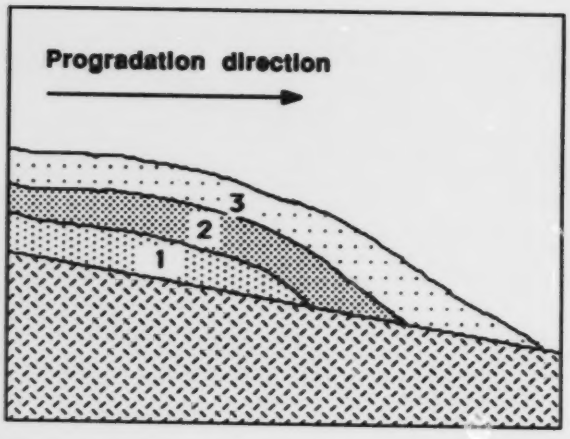


Fig. 5 Progradational deposition - basin fills from basin margins (downlap).

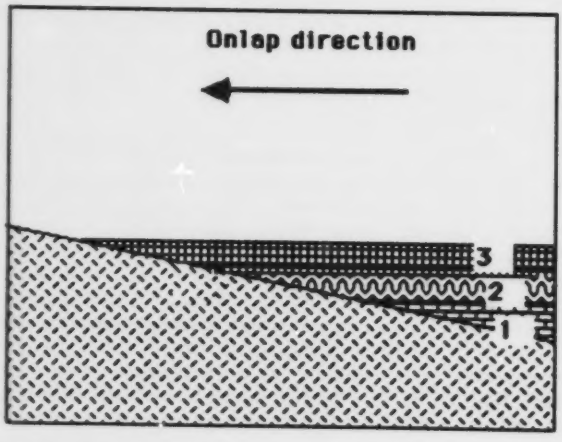


Fig. 6 Aggradational deposition - basin fills from the basin center (onlap).

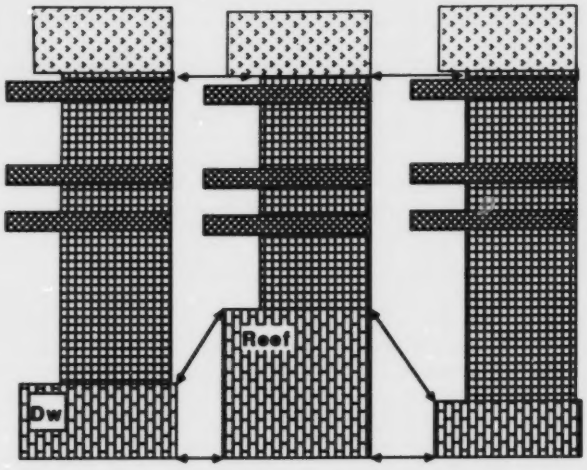


Fig. 7 Thinning pattern (onlap) recognized over the Winnipegosis reefs. Most thinning occurs below the Esterhazy potash bed.

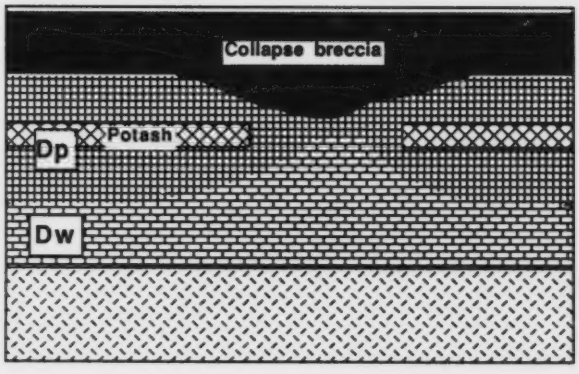


Fig. 8 Dissolution over Winnipegosis reefs. Minor thinning of the Prairie over the reefs and usually the potash beds are missing.

In this scenario, periods of exposure/emergence are characterized by an active groundwater system whose potentiometric head is the driving force causing the groundwater flow and the subsequent dissolution. This plumbing system, over the large hiatuses, provided the adequate volume of water necessary to dissolve the Prairie Formation. In support of this theory, the existence of salt springs in Manitoba has been cited (Cameron, 1949) as evidence for present-day potentiometric flow resulting in Prairie salt dissolution.

Holter (1969) has suggested that Winnipegosis reefs localize dissolution by focusing groundwater (potentiometric) flow into the porous reef facies. Additional impetus is derived from fracturing caused by differential compaction of salt over the Winnipegosis reef certainly raises the question of whether this study, the results suggest that it occurs on a very minor scale or that is is non-existent. As a prerequisite to Winnipegosis-sourced groundwater dissolution, aquifer continuity across the basin is necessary. The isolated nature of the basinal Winnipegosis reefs, certainly raises the question of whether viable fluid transmissivity could occur between the shelf and the reefs. If significant dissolution were related to a Winnipegosis aquifer, thinning over reefs would occur in a bottom to top process. This pattern was not recognized over the reefs.

Several authors have suggested a tectonic control is the primary process localizing dissolution (DeMille et al, 1964; Anderson and Hunt, 1964; Kent, 1968). Thomas (1974) has suggested that the abundant lineaments throughout the Rocky Mountain region are surface manifestations of Precambrian zones of weakness. Two major sets of lineaments occur within the Williston Basin; a northwest and a northeast set (Fig. 9). Thomas believes the northeast lineaments exhibit right-lateral movement while the northwest sets are left-lateral. Brown (1978) and Gerhard et al (1982) suggest that an opposite direction of wrenching better explains the structures within the basin and in the Rocky Mountain province as a whole. During later periods of deformation the individual blocks were subjected to stress fields (of varying orientations) which caused reactivation of those zones of weakness. Since the zones of weakness are superimposed upon the Phanerozoic section during tectonic movements, the zones of deformation are nearly vertically superimposed. Kent (1974) suggested that extensive fracturing along the lineaments may allow for vertical migration of hydrocarbons along the fractured conduits, thereby explaining the potential for sourcing several intervals in the lower Paleozoic (from the Winnipeg) and the upper Devonian (from the Bakken). Similar reasoning would suggest that non-hydrocarbon fluids, primarily water, would also be transmitted along the fractures, contributing to the Prairie dissolution during periods of potentiometric flow and/or basin dewatering. Lateral migration of fluids along these conduits is a viable possibility which probably explains the linearity of many dissolution areas. Correlations between the major tectonic lineaments and areas of salt dissolution suggest that tectonic control on dissolution is a primary factor. A similar zone of weakness may also be inherent along the eastern Prairie salt edge. Here the salt edge is nearly coincident with the Precambrian boundary between the Superior (2.4-2.7 b.y.) and Churchill provinces (1.6-1.8 b.y.) (Sandberg, 1964). Gerhard (1978) has demonstrated that this feature has been tectonically active and acts as a basin hingeline through much of the Phanerozoic.

Dissolution thinning, in contrast to depositional thinning, is usually abrupt, with up to several hundred feet of halite becoming correlative to a much thinner zone of collapse breccia. Correlations across such areas, such as the Roosevelt County, Montana, salt void (T 29 and 30 N, R 57 and 58 W)

Fig. 9 Distribution of some linears, lineations and bedrock trends; Montana, North Dakota, Saskatchewan, Manitoba and Alberta.

indicate that the dissolution process has occurred from the top of the formation downward (Fig. 10). This would suggest that the aquifer supplying the fluids is located upsection of the Prairie and that the Winnipegosis is not involved in this process. Perhaps fracture healing within the plastic evaporites seals the formation from dissolution from below.

EXPLORATION SIGNIFICANCE

This study has documented the aspects in which Prairie Formation depositional thinning and dissolution thinning differ. By applying these concepts to the current Prairie salt edge, it is possible to determine the nature of the salt perimeter. Using the criteria established above, both the western and eastern salt edges are dissolution in origin, whereas the southern basin margin is depositional. By applying the depositonal thinning gradients observed on the eastern and western margins, an original salt depositional edge may be reconstructed. The areas between the current salt edge and the projected edge are areas favourable for dissolution-related structural (Outlook Field) or stratigraphic (Glenburn Field) traps. The southern perimeter would not be a favourable area to prospect for these types of traps. Similarly, because salt dissolution is tectonically sensitive, applying these concepts to exploration along major lineament systems could also prove useful.

CONCLUSIONS

Both differential accumulation of salt during deposition and dissolution of salt are responsible for anomalous thinning within the Prairie Formation. By utilizing several intra-formational Prairie cycles as datums, changes within the Prairie were documented and were found to differ between the two processes. Depositional thinning by onlap is characterized by bottom to top thinning. This was explained by declining accommodation potential (subsidence rates) from the basin center outward. Similarily, depositional thinning by onlap was found to occur over the Winnipegosis reefs.

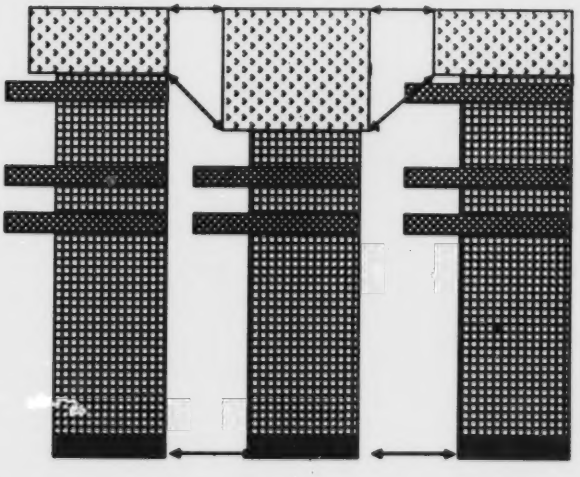


Fig. 10 Schematic cross section showing top down thinning seen over areas of dissolution. Zone overlying the dissolution area contains collapse breccias of the overlying units.

REFERENCES

Anderson, S.B. and Hunt, J.B., 1964, Devonian salt solution in north central North Dakota; In: Third International Williston Basin Symposium, p. 93-104.

Brown, Donald L., 1978, Wrench-style deformational patterns associated with a meridional stress axis recognized in Paleozoic rocks in parts of Montana, South Dakota, and Wyoming; In: The Economic Geology of the Williston Basin, 24th Annual Conference, Montana Geological Society.

Cameron, E. L., 1949, Salt, potash and phosphate in Manitoba: Manitoba Mines Branch, Bull. no. 48-49.

Davis, Thomas L., 1972, Velocity variations around Leduc reefs, Alberta: Geophysics, v. 37, n. 4, p. 584-604.

DeMille, G., Shouldice, J. R., and Nelson, H. W., 1964, Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Geol. Soc. of America Bull., v. 75, p. 307-316.

Gerhard, Lee C., Anderson, Sidney B., Lefever, Julie A. and Carlson, Clarence G., 1982, Geological development, origin, and energy mineral resources of Williston Basin, North Dakota: AAPG Bull., v. 66, no. 8, p. 989-1020.

Holter, M. E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources, Report 123, 133 p.

Illing, L. Y., 1959, Deposition and diagenesis of some Upper Paleozoic carbonate sediments in Western Canada: 5th World Petrl. Cong. Proc, sec. 1, p. 23-52.

Jodry, R. L. 1969, Growth and dolomitization of Silurian reefs, St. Clair County, Michigan: AAPG Bull., v. 53, p. 957-981.

Kendall, A. C., 1984, Evaporites, Chapter 17, In: Facies Models (2nd Edition), Roger G. Walker (ed.), Geoscience Canada, Reprint Series 1, 317 p.

Kent, D. M., 1968, The geology of the Upper Devonian Saskatchewan Group and equivalent rocks in western Saskatchewan: Saskatchewan Dept. of Min. Resources, Rept. No. 98.

Kent, D. M., 1974, The relationship between hydrocarbon accumulations and basement structural elements in the northern Williston Basin, In: Fuels: a geological appraisal, Proceedings of a symposium held on 7-8 November 1974, Saskatchewan Geological Society Special Publication No. 2., p. 63-79.

Mitchum, Jr., R. M., Vail, P. R. and Thompson III, S., 1977, Seismic stratigraphy and global changes of sea level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis; In: Seismic Stratigraphy-applications to hydrocarbon exploration, AAPG Memoir 26.

Peterson, James A. and Hite, Robert J., 1969, Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrence, southern Rocky Mountains: AAPG Bull., v. 53, n. 4, p. 884-908.

Sandberg, Charles A., 1964, Precambrian to Mississippian paleotectonics of the southern Williston Basin; In: Third International Williston Basin Symposium, p. 37-44.

Simpson, Frank, 1978, Plate-tectonic scenario for solution-controlled collapse structures in Paleozoic carbonate-evaporite sequence of the northern Williston Basin region; In: The Economic Geology of the Williston Basin, 24th Annual Conference, Montana Geological Society.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: GSA Bull., v. 74, p. 93-114.

Sloss, L. L. and Speed, R.C., 1974, Relationships of cratonic and continental-margin tectonic episodes, In: Tectonics and Sedimentation, W. R. Dickinson (ed.),: SEPM Spec. Publ. 22, p. 98-119.

MACROFOSSILS AND STRATIGRAPHIC SUBDIVISIONS OF THE BAKKEN FORMATION (DEVONIAN-MISSISSIPPIAN), WILLISTON BASIN, NORTH DAKOTA

LARRY C. THRASHER

U.S. Bureau of Land Management
P.O. Box 1229
Dickinson, ND 58602

ABSTRACT

Well over 500 macrofossils representing more than 50 taxa were collected from 39 cores of the Bakken Formation in North Dakota. Brachiopods, the most common fossils, represent 17 genera, 11 of which have not been previously reported from the Bakken. Nonbrachiopod fossils, mostly not previously reported from the Bakken, include a syringoporid coral, several genera of gastropods and pelecypods, straight and coiled cephalopods, a trilobite, the conchostracan *Cyzicus (Lioestheria)* sp., a shrimp-like organism, trace fossils characterized by *Scalarituba missouriensis*, and *Foerstia* sp. and other plants.

Macrofossils of the Bakken were found mostly within five stratigraphic intervals; each interval contains a different fauna and thus the same vertical sequence of fossils was found from core to core. The basal few feet of the lower shale member locally contains a benthic rhynchonellid fauna that appears similar to fossils from near the base of Devonian black shales in the eastern United States. *Foerstia* sp., found in the basal 20 to 30 per cent of the lower shale member in one core, appears to mark a widespread time-stratigraphic interval of Late Devonian age. *Cyzicus (Lioestheria)* sp. is prolific in the upper few inches of the lower shale near the center of the basin; this species is concentrated at a similar interval in correlatives of the Bakken that crop out in the western interior region. The other fossiliferous intervals of the Bakken occur in the middle member and are found in association with lithologies that are used here to divide the middle member into three stratigraphic units: units 1, 2, and 3. The lowest of these, unit 1, up to about 30 feet thick, contains a *Syringothyris* brachiopod fauna similar to that of the Louisiana Limestone of latest Devonian age in the upper Mississippi Valley and in siltstones of Bakken correlatives in the western United States, also of latest Devonian age. Unit 1 appears to be the only regressive unit in an otherwise transgressive formation. Unit 2 is up to about 35 feet thick and is poorly fossiliferous. Blade-like "leaves" are abundant in the basal few feet of unit 2 near the center of the basin and correlate with similar "leaves" that locally mark the base of the type Mississippian section in Illinois. This correlation, the correlation of the brachiopods in units 1 and 3, and the transgressive nature of unit 2 suggest an early Mississippian age for this unit. The contact between units 1 and 2, although poorly defined, thus appears to mark the systemic boundary in North Dakota. Unit 3, comprising about the top 5 feet of the middle member, contains brachiopods that seem to correlate with those of the McCraney Limestone in the type Mississippian section and the *Spirifer marionensis* fauna of the Exshaw Formation in Alberta, both of early, but not earliest, Mississippian age; this may be the first correlation made between the McCraney and Exshaw. The structural attitudes of unit 3 and the upper shale member suggest that these beds were deposited after a reorientation of the Bakken sea. Macrofossils in the upper shale member are generally small, thin-shelled and rare; no fossiliferous intervals or age-diagnostic fossils were found in this member.

INTRODUCTION

GENERAL

The Bakken Formation, up to 145 feet thick in North Dakota, is a subsurface formation in the Williston Basin that typically consists of three informal members: a lower and an upper shale member, both generally dark-gray to black, carbonaceous, pyritic, and finely laminated, and a middle member of predominantly medium-gray siltstone. Within North Dakota, the lower shale is the least extensive member with the other two members forming a transgressive, onlapping sequence above it. The shales are important petroleum source rocks in the Williston Basin, and their distinctive lithology makes them excellent marker beds for subsurface correlation within the basin.

GEOLOGIC SETTING

The dark shale-light siltstone-dark shale sequence of the Bakken is an example of what was described by Gutschick and Moreman (1967, p. 1012, 1014) as the most common of four general types of lithic sequence that cross the Devonian-Mississippian boundary throughout the North American craton. This tripartite sequence, as noted by Gutschick and Moreman (p. 1009, 1013), occurs around the eastern and western margins of the cratonic platform, in subsiding troughs adjacent to the Transcontinental Arch, and in intracratonic basins, such as the Williston and Michigan Basins. Rock units of this sequence in the eastern and central United States include the Ohio, New Albany, Antrim, and Chattanooga Shales. Gutschick and Moreman (1967, p. 1013) said that the depositional environments of these rocks were affected by the Antler Orogeny along the west coast and the Acadian Orogeny along the east coast, and that effects of these orogenies can be traced into the intracratonic basins. They concluded (p. 1014) that this tectonic framework resulted in the deposition of dark shale-light siltstone-dark shale sequences to occur with a general mirror-like symmetry on each side of the craton.

The location of the rocks of this tripartite sequence in the western interior region is shown on Figure 1. The Exshaw Formation, the Sappington Member of the Three Forks Formation, the Leatham Formation, and the Leatham Member of the Pilot Shale consist of a black shale member overlain by a siltstone member and thus correlate with the lower two members of the Bakken Formation. The Cottonwood Canyon Member of the Lodgepole or Madison Limestone is a black shale unit that overlies the Sappington and Leatham Formation but grades eastward into predominantly carbonate rocks that closely resemble the "lithologic character, stratigraphic relations, thickness, and age" of the Englewood Formation (Sandberg and Klapper, 1967, p. B37). Parts of the Exshaw Formation are overlain by a black shale unit called the basal shale of the Banff Formation; no shale unit overlies the Leatham Member of the Pilot Shale (Gutschick and Rodriguez, 1979).

The lower shale and middle siltstone members of the Bakken are thought (e.g. Penner, 1958; Macqueen and Sand-

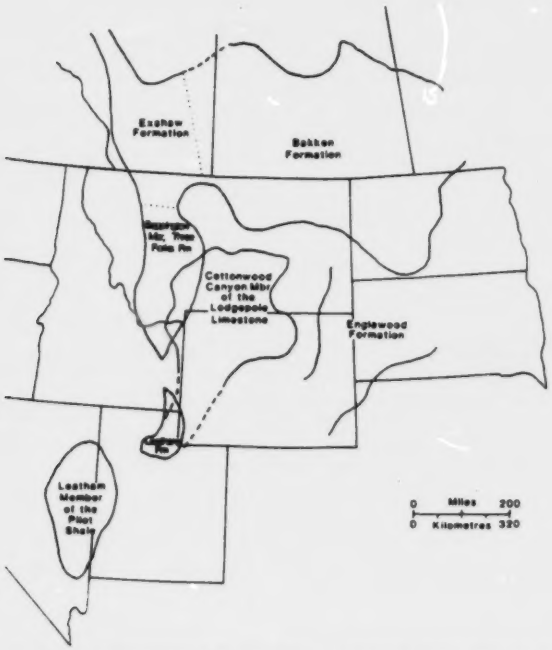


Fig. 1 Approximate areal extent of the Bakken Formation and rocks of equivalent age in the western interior (see text). Adapted from Hayes (1984); primary sources are Christopher (1961) and Meissner (1978) for the Bakken Formation, Macqueen and Sandberg (1970) and Gutschick and Rodriguez (1979) for the Exshaw Formation, the Sappington Member of the Three Forks Formation, the Leatham Formation, and the Leatham Member of the Pilot Shale, Sandberg and Klapper (1967) for the Cottonwood Canyon Member of the Lodgepole or Madison Limestone, and Sandberg and Mapel (1967) for the Englewood Formation.

berg, 1970, p. 41) to be laterally continuous with the corresponding rocks of the Exshaw Formation but, "because of later erosion, the upper black shale of the Bakken now extends only as far west as north-central Montana" (Sandberg and Klapper, 1967, p. B38). The shale member of the Exshaw is, in turn, continuous with the shale member of the Sappington but the siltstone units of the Exshaw and Sappington are now separated by an erosional area about 40 miles wide in northwestern Montana (Sandberg and Klapper, 1967, p. B38). The Sappington Member, the Leatham Formation, and the Leatham Member are thought to be originally continuous rock bodies that were separated by Early Mississippian erosion (Sandberg and Poole, 1977, p. 172).

BIOSTRATIGRAPHY

All of these correlatives of the Bakken in the western interior occur in outcrop and, consequently, have much better biostratigraphic control than does the Bakken Formation. The lithic correlatives of the lower two members of the Bakken form a widespread, vertical sequence of lithofacies and biofacies that "represent extensive, remarkably persistent strike deposition along the geosyncline across western United States into Canada" (Gutschick and Rodriguez, 1979, p. 42). These laterally persistent biofacies include a thin conchostracan bed at the top of the lower black shale members from Nevada to Alberta and a *Syringothyris* brachiopod fauna in the lower parts of the siltstone members of the Sappington Member, the Leatham Formation, and the Leatham Member.

This *Syringothyris* fauna was named after, and has long been correlated with, the *Syringothyris* brachiopod fauna of the Louisiana Limestone in the type Mississippian area of northeastern Missouri and western Illinois. The Louisiana Limestone was originally thought to be the basal part of the Mississippian type section until later conodont evidence presented by Scott and Collinson (1961) demonstrated that the Louisiana is of latest Devonian age. The Louisiana contains a *Protognathodus kockeli* conodont fauna, which is thought to be a carbonate biofacies of the *Siphonodella praesulcata* fauna found in the lithic equivalents of the Bakken siltstone member in the western United States (Sandberg et al, 1972, p. 189-190). Brachiopods of the Exshaw siltstone were also originally correlated with the *Syringothyris* fauna of the Louisiana Limestone (Harker and McLaren, 1958, p. 251); the Exshaw fauna was designated as the "*Spirifer marionensis* zone" by Harker and Raasch (1958, p. 228), who named it after a characteristic species of the Louisiana Limestone. The correlation between the Exshaw and Louisiana later became controversial, however, when early, but not earliest, Mississippian conodonts were recovered from near the base of the Exshaw siltstone member (Macqueen and Sandberg, 1970, p. 47). Thus, the Exshaw siltstone contains brachiopods that resemble the brachiopod fauna of the Louisiana and Sappington but contains conodonts that appear to be much younger than conodonts from those units.

Conodonts have proven to be the primary guide fossils for determining the ages of the dark shale-light siltstone-dark shale sequence in the western interior. Figure 2 shows the conodont zonation scheme of these rocks. Based on a new phylogenetic model of the conodont genus *Palmatolepis* , Ziegler and Sandberg (1984) have revised the upper part of the standard Late Devonian conodont zonation scheme. A conversion chart of the two schemes is shown as Figure 3. Their work was received too late to be incorporated into this study.

PREVIOUS WORK

Biostratigraphic work on the Bakken Formation in the United States consists essentially of conodont studies by Hayes (1984, 1985) and Huber (1986). They found conodonts suggestive of the Upper *Polygnathus styriacus* (Lower *Palmatolepois gracilis expansa*) Biozone of Late Devonian age in the lower shale member and Early Mississippian conodonts in the upper Bakken shale. They recovered few conodonts from the middle member, none of which was age-diagnostic.

Macqueen and Sandberg (1970, p. 52) reported that the micropaleontological evidence for the correlation of the Bakken in Canada is limited to two cores from southeastern Alberta; one of these contained Late Devonian conodonts in the lower shale member and the other contained palynomorphs in the middle member that have been identified as belonging to the *Spelaeotriletes lepidophytus* assemblage. This spore assemblage, whose range crosses the systemic boundary, has also been reported from the upper part of the siltstone beds (unit G) of the Sappington Member (Macqueen and Sandberg, 1970, p. 51).

The only study that has treated the macrofossils of the Bakken in any detail, apparently, is by Brindle (1960), who listed eight types of brachiopods from the middle member in Saskatchewan and illustrated four of them. These brachiopods have been widely correlated (Christopher, 1961; Gutschick and Moreman, 1967) with the *Syringothyris* fauna of the Louisiana Limestone, and this correlation serves as the primary basis for the age determination of the middle member of the Bakken Formation.

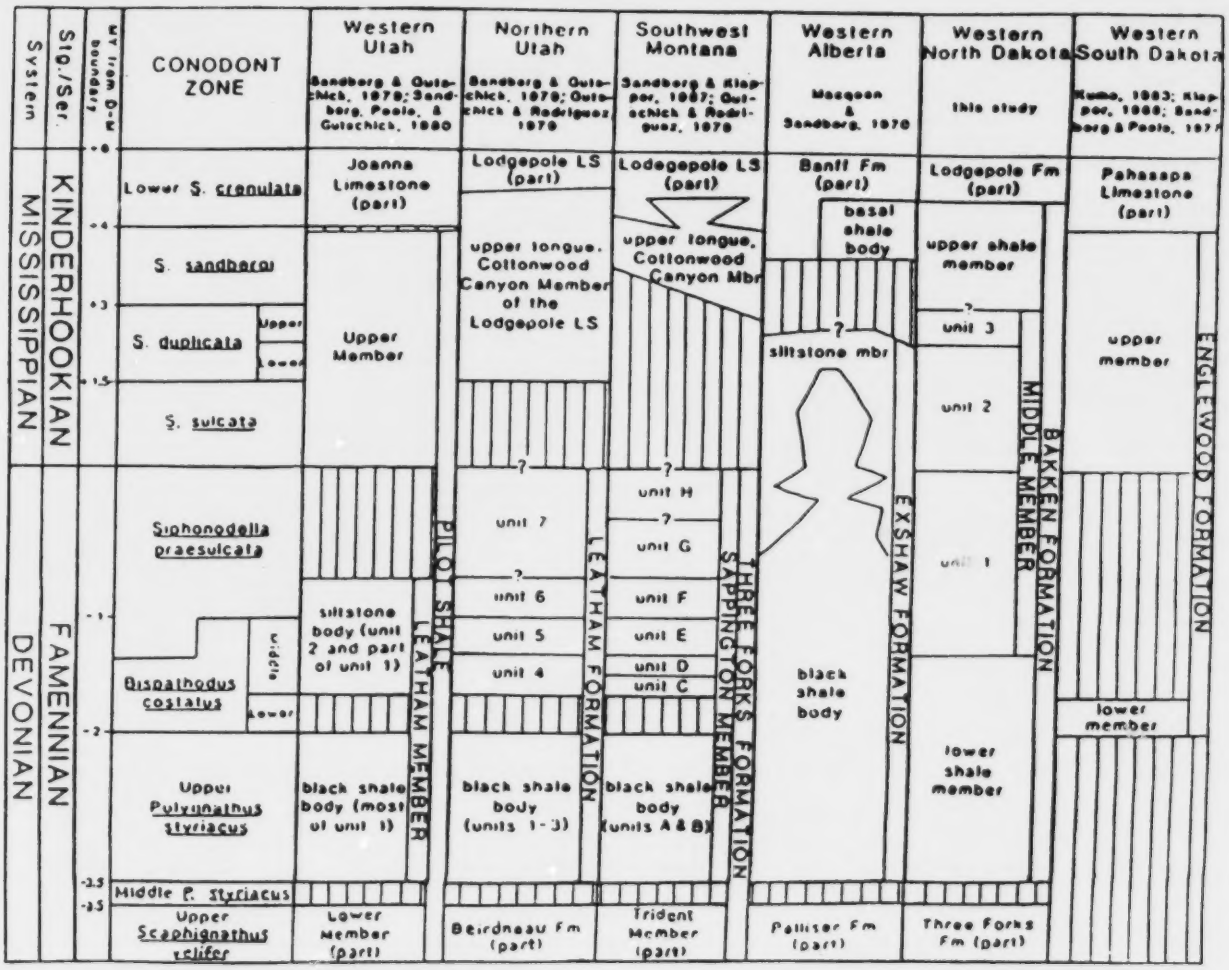


Fig. 2 Correlation chart of the Bakken Formation and rocks of equivalent age in the western interior (see text). The timespans given are those of Sandberg et al (1983), and are based on conodont evolutionary rates; they noted (p. 695) that the currently accepted age for the Devonian-Mississippian boundary is about 360 million years before the present.

FORMER CONODONT ZONATION Sandberg, 1979		CURRENT CONODONT ZONATION Ziegler and Sandberg, 1984	
SIPHONODELLA PRAESULCATA	*Upper	SIPHONODELLA PRAESULCATA	Upper
	Middle		Middle
BISPATHODUS COSTATUS	Lower		Lower
	Upper	PALMATOLEPIS GRACILIS EXPANSA	Upper
POLYGNATHUS STYRIACUS	Middle		Middle
	*Lower		Lower
	Upper	PALMATOLEPIS PERLOBATA POSTERA	Upper
SCAPHIGNATHUS VELIFER	Middle		Lower
	*Lower	PALMATOLEPIS RUGOSA TRACHYTERA	Uppermost
PA. MARGINIFERA MARGINIFERA	Upper	PALMATOLEPIS MARGINIFERA MARGINIFERA	Upper
	Lower		Lower

Fig. 3 Previous and current standard conodont zonation schemes of Upper Devonian (middle to latest Famennian) rocks. Asterisked zones are those not recognized in the western interior region (Sandberg et al, 1983, p. 694).

MATERIALS AND METHODS

This study is based on cores from 39 wells that cored all or part of the Bakken Formation. Twenty-six of these cores yielded fossils. Those that did not are mostly in poor condition or represent a small portion of the formation. The well locations and identifying North Dakota Geological Survey well file numbers (NDGS 105) are shown on Figure 4. The Bakken is up to about 140 feet thick in cores from the central part of the basin and thins out evenly to about 10 feet thick in cores from near the margins of the formation. Only three cores (not including those from near the margins) were found that contained the complete Bakken section. The lower shale member, up to 50 feet thick, was found in 33 of the cores, the middle member, up to 70 feet thick, in 24, and the usually thin (up to 25 feet thick) upper shale was present in 16 cores. In all, nearly 1500 feet of Bakken core were examined.

The lithology of the cores was described, and the depth and orientation of each fossil found were noted. Standard paleontological techniques were used to prepare the fossils for their identification and illustration. Fossils were identified by researching the literature.

Table 1. NAME AND LOCATION OF CORES USED IN THIS STUDY.

Well No.	Operator	Well Name	Q/Q	S-T-R	County
105	Stanolind Oil and Gas Co.	Walter and Ingerborg Wanvick No. 1	SW/NE	2-153-83	Ward
413	Carter Oil Co.	Edward Lockwood Jr. No. 1	SE/SW	5-147-93	Dunn
527	California Oil Co.	Rough Creek Unit No. 1	NW/NE	13-148-98	McKenzie
607	Socony-Vacuum Oil Co.	Angus Kennedy No. F 32-24-0	SW/NE	24-149-93	Dunn
793	Mobil Production Co.	Solomon Bird Bear No. 1	SE/NW	22-149-91	Dunn
999	Texaco, Inc.	J. N. Donohue No. 1	SW/NE	23-154-100	Williams
1202	Amerada Petroleum Co.	Jane Strand No. 1	SW/NW	6-152-94	McKenzie
1254	Northern Pump Co.	Gilbert T. Rhode No. 1	SW/SE	17-152-94	McKenzie
1343	Pan American Petroleum Corp.	Helen G. Price No. 3	NW/SW	7-152-94	McKenzie
1405	Cofer Oil, Inc.	Catherine E. Peck No. 2	NW/NE	27-150-96	McKenzie
1606	Amerada Petroleum Corp.	H. H. Shalvik Tract 1, No. 1	NE/SW	35-150-97	McKenzie
1679	Amerada Petroleum Corp.	C. C. Hagen Tract 1, No. 1	SW/SE	10-153-96	McKenzie
1748	Amerada Petroleum Corp.	Reed-Norby Unit No. 1	NW/NE	6-152-94	McKenzie
1858	Amerada Petroleum Corp.	Minnie Kummer Tract 1, No. 1	NW/NE	25-150-96	McKenzie
1886	Amerada Petroleum Corp.	John Dimondale No. 1	NW/SE	33-153-94	McKenzie
2226	Amerada Petroleum Corp.	USA Thomas No. 1	SW/NW	18-153-94	McKenzie
2383	Gulf Oil Corp.	Lawrence Bird's Hill No. 1	NW/NE	30-150-94	McKenzie
2602	Texaco, Inc.	Garland No. 5	SW/NE	6-153-95	McKenzie
2618	Pan American Petroleum Corp.	Jacob Huber No. 1	SW/SE	15-145-91	Dunn
2820	Texaco, Inc.	F. D. Keough No. 1	NW/SW	5-151-95	McKenzie
2828	Texaco, Inc.	L. J. Novak No. 1	NW/NW	15-154-98	Williams
2967	Texaco, Inc.	A. S. Wiseman No. 2	NW/SE	3-152-96	McKenzie
3007	Dallas Petroleum Corp.	Hamlet Unit No. 2	C/NE	30-159-95	Williams
3167	Texaco, Inc.	W. Quale No. 1	SE/SW	31-153-95	McKenzie
3363	Texaco, Inc.	Clarence Pederson (MCY-1) No. 1	NW/SE	19-157-98	Williams
4113	Texaco, Inc.	Fort Berthold Allottees 437 No. 1-A	SE/NW	4-150-93	Mountrail
4264	Texaco, Inc.	Devonian Unit No. 5, Well No. 1	NE/NW	3-153-95	McKenzie
4297	Pan American Petroleum Corp.	B. E. Hove No. 1	SW/NE	2-154-95	Williams
4340	Pan American Petroleum Corp.	Clifford Harmon No. 1	SW/SW	2-154-95	Williams
4508	Northern Pump Co.	Louis Peterson No. 1	NE/NE	7-161-90	Burke
4958	John B. Hawley Jr. Trust No. 1	Florence M. Ingerson No. 2	SW/NE	2-161-91	Burke
5088	Shell Oil Co.	Shell-Texel No. 21-35	NE/NW	35-156-93	Mountrail
7579	Shell Oil Co.	USA No. 42-24A	SE/NE	24-145-104	McKenzie
7851	Brooks Exploration, Inc.	Bogstad No. 1-11	NE/SE	11-155-91	Mountrail
7887	Texaco Oil Co.	Moe USA No. 3-17	SW/NE	17-142-100	Billings
8069	Marathon Oil Co.	Jensen No. 12-44	SE/SE	12-154-90	Mountrail
8177	Marathon Oil Co.	Dobrinski No. 18-44	SE/SE	18-151-87	Ward
8474	Texaco Oil Co.	Graham USA No. 1-15	NE/SW	15-144-101	Billings
9351	Supron Energy Corp.	Federal No. 3	NW/SE	6-144-101	Billings

RESULTS

More than 500 macrofossils were collected from the cores of the Bakken Formation in North Dakota. These were found to represent more than 50 taxa, 25 of which are brachiopods identified at least to genus. Nonbrachiopod fossils are a hylothyrid, a syringoporid coral, several genera of gastropods and pelecypods, straight and coiled cephalopods, a trilobite, the conchostracan *Cyzicus (Lioestheria)* sp., a shrimp-like organism, pelmatozoan columnals, fish fragments, *Foerstia* sp. and other plants, and trace fossils.

Almost all of the fossils of this study were found within five stratigraphic intervals of the Bakken (Figs. 5 and 6). Each of these intervals contains a different fauna and thus the same vertical sequence of fossils was found from core to core. Two of these fossiliferous intervals are in the lower shale member and the other three are in the middle member. Those in the middle member occur in association with distinctive lithic changes that are used here to divide this member into three informal stratigraphic units: units 1, 2 and 3 for the lower, middle, and upper parts of the member, respectively.

LOWER BAKKEN SHALE

The fossiliferous intervals in the lower shale member are in dark-gray to black shales that, aside from the fossils, are indistinguishable from the rest of the member. The fossils in both shale members of the Bakken are preserved as flattened molds of the interior or, less commonly, as carbonaceous impressions. Some have been partly replaced by pyrite or, less commonly, by other sulfides.

The stratigraphically lowest fossiliferous interval of the Bakken is a benthic rhynchonellid brachiopod fauna within the basal few feet of the lower shale member. Although locally abundant, macrofossils were typically rare or, more commonly, absent in this interval. Fossils were found in six (NDGS 527, 607, 1679, 2226, 2383, and 5088) of the 18 cores of this interval, and were common in three. Fossils from this lowest interval consist of a hylothyrid, *Lingula* sp. 2 (Pl. 1, Fig. 6) *Barroisella* sp., *Rugaltarostrum montanensis* (Pl. 1, Figs. 9, 10), fragments of small, costate rhynchonellids, *Phragmosphaera* sp., *Straparollus (Straparollus)* sp. 2, a straight cephalopod, a coiled cephalopod, what appear to be several species of pelecypods, the conchostracan *Cyzicus (Lioestheria)* sp. (Pl. 1, Fig. 14),

Table 2. Formation and member tops of cores used in this study. Well numbers are those of the North Dakota Geological Survey. Tops were picked from well logs and are given in feet below Kelly Bushing. Footages for the cored intervals are given in drillers' depths, which commonly differ slightly from the well-log depths. The number of feet to be added to or subtracted from the core depth to obtain the well-log depth is shown in the last column. A hyphen in that column means the two depths are the same. Stratigraphic unit abbreviations are: Ubs = upper black shale member of the Bakken; Mm = middle member of the Bakken; Lbs = lower black shale member of the Bakken; TF = Three Forks Formation.

Well No.	Ubs	Mm	Lbs	TF	Bakken Core Interval	Adj.
105	7552	7556	7569	7578	7552-7562	-
413	10389	10407	10452	10467	10391-10469	-2
527	11195	11213	11254	11283	11225-11295	-12
607	10510	10526	10576	10606	10508-10610	+2
793	9994	10014	10046	10076	9992-10072	+2
999	10928	10948	10985	11012	10984-11026	-14
1202	10267	10287	10331	10356	10257-10343	+10
1254	10373	10393	10433	10457	10450-10453	+4
1343	10266	10287	10326	10350	10340-10346	+4
1405	10737	10762	10784	10823	10759-10820	+3
1606	10872	10904	10950	10964	10945-10966	-2
1679	9904	9922	9976	10004	10003-10011	-7
1748	10644	10667	10716	10748	10720-10753	-5
1858	10884	10908	10952	10974	10963-10972	+2
1886	10613	10633	10690	10722	10701-10716	+6
2226	10485	10512	10559	10601	10578-10590	+11
2383	10667	10683	10724	10757	10750-10758	-1
2602	9707	9730	9775	9802	9789-9801	+1
2618	9776	9793	9826	9838	9794-9839	-1
2820	10569	10589	10630	10655	10587-10634	+2
2828	11050	11068	11114	11141	11132-11143	-2
2967	10225	10246	10288	10315	10238-10307	+8
3007	9403	9412	9476	9506	9409-9438	-
3167	10180	10200	10244	10269	10198-10267	+2
3363	10130	10143	10202	10228	10213-10223	+5
4113	10648	10666	10709	10737	10721-10742	-5
4264	9934	9957	10006	10035	10023-10033	+2
4297	9905	9926	9989	10030	9895-9910	+12
4340	9895	9916	9978	10024	9886-10015	+9
4508	7492	7502	7542	7570	7503-7552	-
4958	7570	7580	7623	7652	7577-7624	-1
5088	10161	10177	10245	10295	10156-10290	+5
7579	10852	10857	-	10864	10856-10869	-3
7851	9370	9385	9419	9453	9386-9450	+3
7887	10794	10800	10808	10810	10786-10802	+8
8069	9157	9174	9207	9237	9157-9211	-
8177	8622	8638	8661	8674	8629-8667	-1
8474	10365	10374	10378	10381	10359-10375	+6
9351	10462	10471	10482	10483	10449-10470	+13

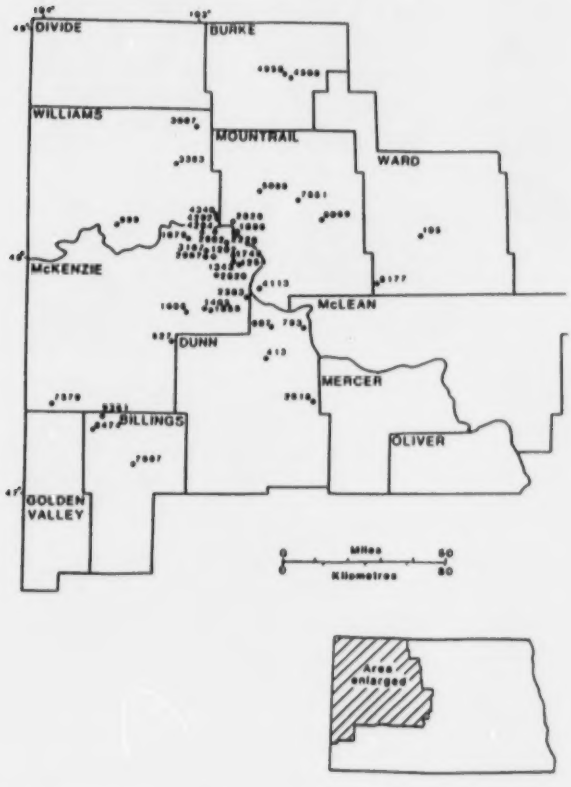


Fig. 4 Location of wells used in this study. Well numbers are those of the North Dakota Geological Survey. The name, operator, and locality of each well is given in Table 1.

fish scales, and one occurrence of a *Spirophyton*-like trace fossil. Conchostracan valves and lingulaceans are the most common macrofossils of this interval and are locally concentrated on bedding planes.

Except for a report of *Rugaltarostrum madisonense* from the basal few feet of the Sappington by Sartenaer (1967), macrofossils have generally not been reported from near the base of the lower black shales in the western interior. This fauna in the Bakken does, however, resemble a *Leiorhynchus* fauna found locally in the Blocher Formation of the New Albany Shale and equivalent rocks near the base of the Devonian black shales in the east-central United States. Ettensohn and Barron (1981, p. 350) suggested that this fauna in the eastern shales was deposited during the initial phase of a transgression "in water shallow enough to allow vertical mixing and replenishment of oxygen . . . ". The fauna in the Bakken, like that in the eastern black shales, consists entirely of epibenthic forms; no evidence of infaunal forms was noted in this interval of the Bakken. Ettensohn and Barron (p. 350) suggested that a lack of infauna in the eastern shales is evidence that "reducing conditions rapidly set in below the sediment-water interface."

The other fossiliferous interval of the lower shale member is a proliferation of single valves of *Cyzicus (Lioestheria)* sp. within the top few inches of this member. These conchostracan valves are thin, generally crushed, and lie flat on bedding planes of dark, carbonaceous shale (Pl. 1, Fig. 13). The valves were found in eight of the fourteen cores found that have the top few inches of the lower shale member. They appear to mark a persistent biosome in and near the area mapped by Webster (1982, p. 20) as being the depocenter of the lower black shale but, as shown on Figure 7, they seem to be confined to that area, perhaps due to later erosion of this bed. The only other macrofossil found within this biosome is one carbonaceous impression of the posterior portion of a shrimp-like organism.

The conchostracan bed of the Bakken is faunally, lithologically, and stratigraphically nearly identical to the conchostracan bed of the Exshaw Formation, the Sappington Member, the Leatham Formation, and the Leatham Member. Conodont evidence (Sandberg and Poole, 1977, p. 172) suggests that this conchostracan bed in the western United States is of very late Devonian age and is essentially isochronous. Macqueen and Sandberg (1970, p. 52-53), however, reported that one conodont collection from the conchostracan bed in the Exshaw contains *Siphonodella cooperi* and other conodonts of undoubted Mississippian age; thus they suggested that this conchostracan bed in the western interior is time-transgressive. The conchostracan bed of the Bakken appears to be of the same Late Devonian age as the correlatives in the United States, as is evidenced by the presence of species of the latest Devonian *Syringothyris* fauna in the overlying rocks of the middle member and the fact that Hayes (1984) found Upper Devonian conodonts within the top few inches of the lower shale member in North Dakota.

Outside of these two fossilferous intervals, macrofossils are rare in the lower black shale; those found consist of one lingulid valve, one small, straight cephalopod, possible ostracod-like valves up to 6 mm long (Pl. 1, Fig. 10), disarticulated fish fragments, and two possible plant stems. Also, numerous thalli of *Foerstia* sp. (Pl. 1, Figs. 8, 12) were found in a short section of one core from near the center of the basin (NDGS 4340). *Foerstia* sp. is an important Late Devonian guide fossil in the east-central black shales, such as the Antrim, Chattanooga, New Albany, and Ohio Shales (Russel, 1985). This supposed pelagic algal form occurs between one-seventh and two-fifths of the way up from the base of those black shale sequences "regardless of the total thickness of those beds" (Mathews, 1983, p. 329). This specific positioning, in conjunction with similar specific positioning of paracontinuous, conodont-bearing lag sandstones in the black shales, demonstrates that these beds, "and thus these shale sequences themselves, are not time transgressive" (Conkin et al, 1980, p. 3). The Bakken specimens were also found within this same stratigraphic level (the bottom 20 to 30 per cent of the lower shale member) and seem to represent a geographic extension of a widespread time marker of Late Devonian age. This suggests that the Bakken is a partial age equivalent of the black shale member of the Exshaw Formation (Cross, 1982) and of many of the Late Devonian black shales in the east-central United States.

MIDDLE BAKKEN SILTSTONE, SANDSTONE AND RELATED SEDIMENTARY ROCKS

The middle member of the Bakken is subdivided into stratigraphic units 1, 2, and 3 on paleontological and lithological grounds. Units 1 and 3 consist of mostly massive, fossiliferous siltstone or silty limestone, and unit 2 is a relatively thick, generally unfossiliferous sequence of thin, intercalations beds of shale, siltstone, and sandstone. Fossils of the middle member are fairly well preserved, although most are slightly crushed and few internal structures were found.

Unit 1 of the middle member is up to about 30 feet thick and typically comprises the basal 40 per cent of the member. This

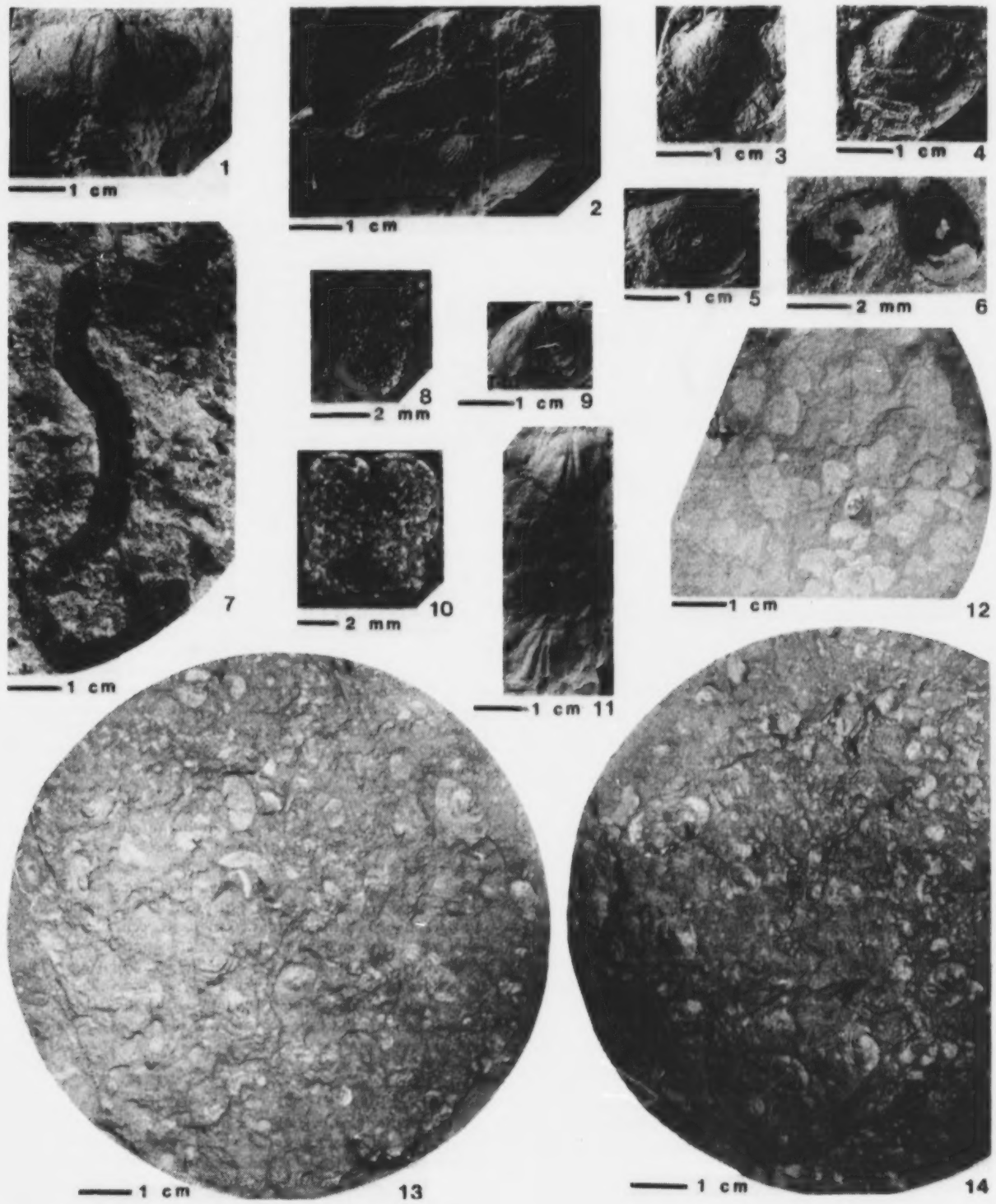


Plate 1. Fossils from the lower shale member and unit 1 of the middle member of the Bakken Formation in North Dakota. The first number after each figure description is the NDGS well number of the core from which the fossil was taken and the second number is the UND catalog number of the specimen. 1) *Syringothyris hannibalensis*, brachial valve, unit 1, 3167, 2769. 2) *S. hannibalensis*, brachial valve and broken posterior [illegible] dicle valve, unit 1, 8069, 2772. 3) *Rhipidomella missouriensis*, pedicle valve, unit 1, 3167, 2741. 4) *R. missouriensis*, brachial valve, unit 1, 4958, 2740. 5) *Rhytiophora arcuata*, brachial valve, [illegible], 8069, 2759. 6) *Lingula* sp., 607, 2733. 7) *Scalarituba missouriensis*, unit 1, 5088, 4351. 8) *Foerstia* sp., small, bifurcating thallus, lower shale member, 4340, 2799. 9) *Rugaltarostrum madisonense*, pedicle [illegible]alve, lower shale member, 2383, 2761. 10) Pyritized ostracod-like valves, lower shale member, 4340, 2796. 11) *R. madisonense*, rubber cast of two brachiopod valves, lower shale member, 1679, 2762. 12) *Foerstia* sp., numerous ovate to bilobed thalli on bedding plane, lower shale member, 4340, 4344. 13) *Cyzicus (Lioestheria)* sp., conchostracan bed from the top of the lower shale member, 1679, 2762. 14) Concentration of *C. (Lioestheria)* sp. from near the base of the lower shale member, 5088, 2793.

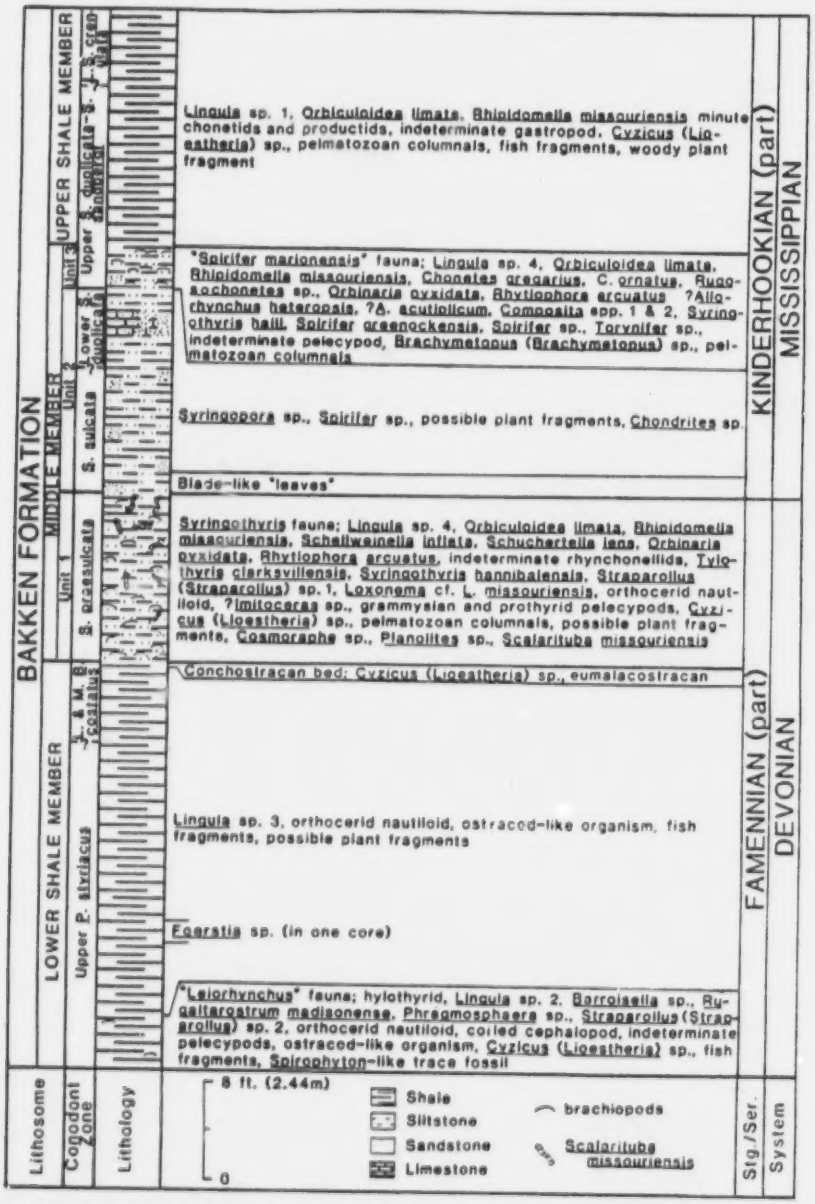

BAKKEN FORMATION
UPPER SHALE MEMBER
MIDDLE MEMBER
LOWER SHALE MEMBER
Unit 3
Unit 2
Unit 1
Upper S. duplicata–S. sinuosa Zone
Lower S. duplicata Zone
S. sulcata
S. crassisulcata
Upper P. styriacus
P. s. & M. B. costatus
KINDERHOOKIAN (part)
FAMENNIAN (part)
MISSISSIPPIAN
DEVONIAN
Lingula sp. 1, Orbiculoidea limata, Rhipidomella missouriensis minute chonetids and productids, indeterminate gastropod, Cyrtina (Ligastheria) sp., pelmatozoan columnals, fish fragments, woody plant fragment
"Spirifer marionensis" fauna; Lingula sp. 4, Orbiculoidea limata, Rhipidomella missouriensis, Chonetes gregarius, C. ornatus, Rugosochonetes sp., Orbinaria pyxidata, Rhytiophora arcuatus, ?Allorhynchus heteropsis, ?A. acutilicum, Composita spp. 1 & 2, Syringothyris hall, Spirifer greenockensis, Spirifer sp., Torynifer sp., indeterminate pelecypod, Brachymetopus (Brachymetopus) sp., pelmatozoan columnals
Syringopora sp., Spirifer sp., possible plant fragments, Chondrites sp.
Blade-like "leaves"
Syringothyris fauna; Lingula sp. 4, Orbiculoidea limata, Rhipidomella missouriensis, Schellweinella inflata, Schuchertella lens, Orbinaria pyxidata, Rhytiophora arcuatus, indeterminate rhynchonellids, Tylothyris clarksvillensis, Syringothyris hannibalensis, Straparollus (Straparollus) sp. 1, Loxonema cf. L. missouriensis, orthocerid nautiloid, ?Imitoceras sp., grammysian and prothyrid pelecypods, Cyrtina (Ligastheria) sp., pelmatozoan columnals, possible plant fragments, Cosmorophe sp., Planolites sp., Scalarituba missouriensis
Conchostracan bed; Cyrtina (Ligastheria) sp., eumalacostracan
Lingula sp. 3, orthocerid nautiloid, ostracod-like organism, fish fragments, possible plant fragments
Eqarstis sp. (in one core)
"Leiorhynchus" fauna; hylothyrid, Lingula sp. 2, Barroisella sp., Rugaltarostrum madisonense, Phragmosphaera sp., Straparollus (Straparollus) sp. 2, orthocerid nautiloid, coiled cephalopod, indeterminate pelecypods, ostracod-like organism, Cyrtina (Ligastheria) sp., fish fragments, Spirophyton-like trace fossil
Lithosome
Conodont Zone
Lithology
8 ft. (2.44m)
0
Shale
Siltstone
Sandstone
Limestone
brachiopods
Scalarituba missouriensis
Stg./Ser.
System

Fig. 5 Composite core section showing the stratigraphic distribution of the macrofossils of the Bakken Formation in western North Dakota. Thicknesses of the rock units are based on those of the type section. Conodont zones are those of Sandberg, 1979.

unit consists mostly of light- to dark-gray, brownish gray, or light- to medium-greenish gray, fossiliferous, bioturbated, and pyritic siltstone that, in places, is dolomitic or grades into silty limestone. Bedding is rare and is generally comprised of distorted or disrupted beds of sandstone up to several inches thick.

The assemblage of unit 1 consists mostly of calcitic brachiopods that are numerically dominated by *Rhipidomella missouriensis* (Pl. 1, Figs. 3, 4). Trace fossils are common, especially in the upper part of unit 1, where abundant trails of *Scalarituba missouriensis* (Pl. 1, Fig. 7) are found. The calcitic fossils are common in the lower one-half of the unit and rare in the upper one-half. The trace fossils occur in almost direct inverse proportion to this, being rare in the lower one-half of the unit and common in the upper one-half. Besides *R. missouriensis*, the brachiopods found in unit 1 consist of *Lingula* sp. 4, *Orbiculoidea limata*, *Schellweinella inflata*, *Schuchertella lens*, one possible immature chonetid, *Orbinaria pyxidata*, *Rhytiophora arcuata* (Pl. 1, Fig. 5), fragments of costate rhynchonellids, *Tylothyris clarksvillensis*, and *Syringothyris hannibalensis* (Pl. 1, Figs. 1, 2). Nonbrachiopod fossils (other than the trace fossils) are relatively rare and were found solely in the basal few feet of the member. They consist of *Loxonema* cf. *L. missouriensis*, minute, pyritized molds of gastropods assigned to *Straparollus (Straparollus)* sp. 1, an orthoconic cephalopod similar to the one in the lower shale, a juvenile goniatite, grammysian and prothyrid pelecypods,

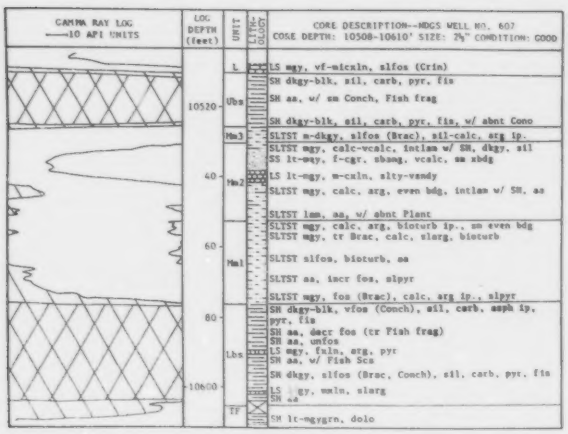

GAMMA RAY LOG
10 API UNITS
LOG DEPTH (feet)
UNIT
LITHOLOGY
CORE DESCRIPTION--NDGS WELL NO. 607
CORE DEPTH: 10508-10610' SIZE: 2⅞" CONDITION: GOOD
10520
40
60
80
10600
L
Ubs
Mm3
Mm2
Mm1
Lbs
TF
LS mgy, vf-micxln, slfos (Crin)
SH dkgy-blk, sil, carb, pyr, fis
SH aa, w/ sm Conch, Fish frag
SH dkgy-blk, sil, carb, pyr, fis, w/ abnt Cono
SLTST m-dkgy, slfos (Brac), sil-calc, arg lp.
SLTST mgy, calc-vcalc, intlam w/ SH, dkgy, sil
SS lt-mgy, f-cgr, sbang, vcalc, sm xbdg
LS lt-mgy, m-cxln, slty-vsndy
SLTST mgy, calc, arg, even bdg, intlam w/ SH, as
SLTST lam, aa, w/ abnt Plant
SLTST mgy, calc, arg, bioturb lp., sm even bdg
SLTST mgy, tr Brac, calc, slarg, bioturb
SLTST slfos, bioturb, as
SLTST aa, incr fos, slpyr
SLTST mgy, fos (Brac), calc, arg lp., slpyr
SH dkgy-blk, vfos (Conch), sil, carb, asph lp, pyr, fis
SH aa, decr fos (tr Fish frag)
SH aa, unfos
LS mgy, fxln, arg, pyr
SH aa, w/ Fish Scs
SH dkgy, slfos (Brac, Conch), sil, carb, pyr, fis
LS gy, mxln, slarg
SH aa
SH lt-mgygrn, dolo

Fig. 6 Core description of NDGS 607. Lithic abbreviations are after Mitchell and Maher (1957). The core depth shown is only of the Bakken Formation and does not include the portions of the subjacent and superjacent formations also shown. Abbreviations for the stratigraphic units are: TF = Three Forks Formation; Lbs and Ubs = lower and upper black shale members, respectively, of the Bakken; Mm1, Mm2, and Mm3 = units 1, 2, and 3, respectively, of the middle member; and L = Lodgepole Formation.

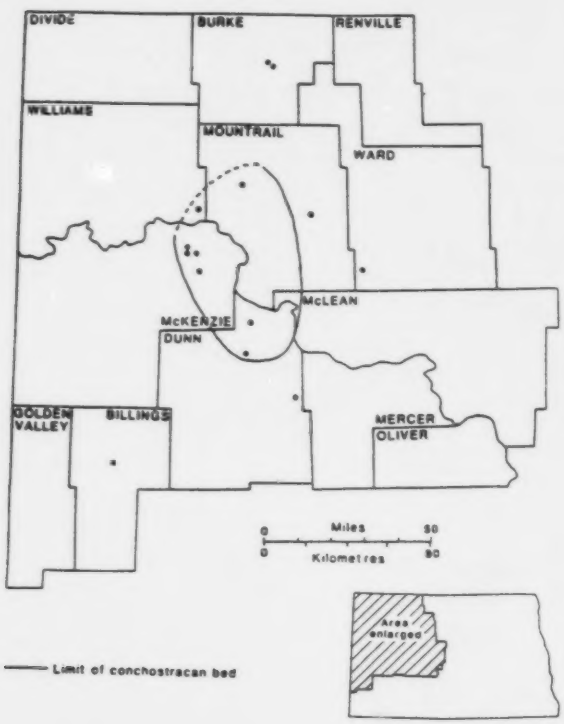


Fig. 7. Areal distribution of the conchostracan bed of the Bakken Formation. Control points represent all cores found that contain the top few inches of the lower shale member.

ostracods, one unflattened valve of *C. (Lioestheria)* sp., fragments of pelmatozoan columns, and one possible plant stem. Juvenile brachiopods were collected along with the minute gastropods and the juvenile goniatite from the residues of hydrochloric acid baths. Small, carbonaceous twig-like fossils were also found throughout unit 1. The trace fossils of unit 1 consist of *Scalarituba missouriensis* in close association with a small, inconspicuous *Cosmoraphe* sp., and rarely found, simple, isolated tubes assigned to *Planolites*.

All of the brachiopods found in unit 1 of the middle member have been reported from the *Syringothyris* fauna of the Louisiana Limestone of Missouri by Williams (1943) or from the *Syringothris*-bearing rocks in the western United States by Gutschick and Rodriguez (1967, 1979); most have been reported from both of these rock bodies. Although most of the nonbrachiopod taxa of unit 1 were not specifically identifiable, they and (especially) the trace fossils closely resemble the nonbrachiopod fauna of the Louisiana Limestone and the correlatives of the Bakken siltstone in the western United States.

The brachiopods of unit 1 are randomly oriented and most are disarticulated; this suggests their post-mortem current transport followed by rapid burial (e.g. storm deposition). Rapid sedimentation in this part of the Bakken is further suggested by the lack of an epifauna on the shells. An epifauna commonly occurs on shells from unit E of the Sappington Member and unit 5 of the Leatham Formation (Rodriguez and Gutschick, 1975) but is not present on shells from the Leatham Member of the Pilot Shale. This absence was attributed by Gutschick and Rodriguez (1977, p. 198) to rapid sedimentation and burial of the shells. Rapid sedimentation would also account for the lack of oncolites in unit 1. Oncolites, closely associated with the *Syringothyris* fauna of unit E of the Sappington Member, unit 5 of the Leatham Formation, and of the Latham Member in Utah (but not in Nevada), are indicative of slow deposition since they require time to develop prior to burial (Gutschick and Rodriguez, 1979, p. 47).

Unit 2 of the middle member, up to about 35 feet thick, typically comprises about 50 per cent of the middle member, and consists mostly of thin, unfossiliferous beds of shale, siltstone, and sandstone (Fig. 8). These beds display numerous, well defined, primary bedding features such as cross bedding, current-bedding, scour surfaces, cut-and-fill structures, and ripple marks. The shales of unit 2 are typically dark gray to black and siliceous; the siltstones are medium gray and slightly calcareous, and the sandstones are mostly light gray, very fine grained, and calcareous. One unusually thick bed of light-gray, fine- to coarse-grained, and very calcareous sandstone or sandy limestone, up to about 10 feet thick, was found in the upper half of unit 2 in many of the cores. This sandy bed (Fig. 9) typically contains many primary bedding structures, locally grades into an oolitic limestone, and is the only bed of the middle member in this study recognizable on well logs (Fig. 6).

Although fossils were generally absent in unit 2, a thin (up to about four feet thick) fossiliferous interval occurs at the base of the unit. The fossils of this interval consist of numerous carbonaceous impressions of blade-like "leaves" that lie flat on thin, well defined, bedding planes. These plants (Pl. 2, Fig. 10) are generally poorly preserved and inconspicuous, and were found on just one bedding plane in some cores. They occur in seven (NDGS 413, 607, 1202, 1405, 2967, 3167, and 5088) of the fifteen cores that contain this interval, and seem to form a laterally persistent biosome (Fig. 10) in much the same area as the conchostracan bed. Like that bed, they appear to be confined to the area near the depocenter of the middle member, as mapped by Webster (1982, p. 21). This general area is apparently where the Bakken reaches its maximum stratigraphic development.

Other fossils from unit 2 consist of a syringoporid coral and *Spirifer* sp. from one core piece near the bottom of the unit; and four stem-like fossils and two occurrences of the trace fossil *Chondrites* from near the top of the unit.

Fig. 8 Slab photo of the interbedded sandstones, siltstones, and shales of unit 2 of the Bakken Formation (NDGS 4340 at 9,932').

Fig. 9 Slab photo of the thick, sandy bed of unit 2 of the Bakken Formation (NDGS 4340 at 9,924').

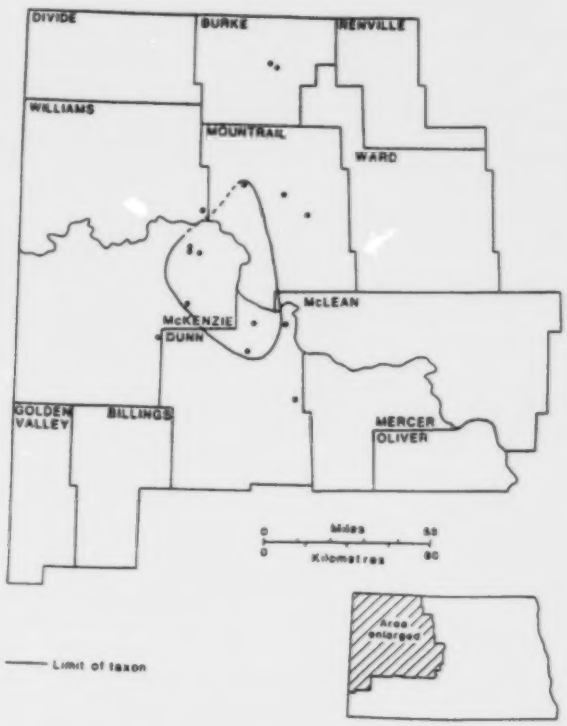


Fig. 10 Areal distribution of the blade-like "leaves" of unit 2 of the Bakken Formation. Control points represent all cores found that contain the basal few feet of unit 2.

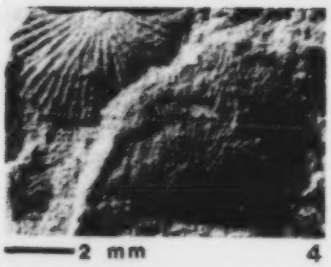
The blade-like leaves of unit 2 appear to correlate with an abundance of "carbonized compressions of fragmentary blade-like "leaves" . . . in thinly laminated, limy, argillaceous, dolomitic and/or silty shales" reported by Conkin and Conkin (1973, p. 25) to occur within the basal few feet of the Horton Creek Member (also known as the Glen Park member) of the Hannibal Formation in western Illinois. The plants in Illinois have been used by Conkin and Conkin (1973, p. 25) to mark the base of the Mississippian in the type Mississippian area, thus indicating that these plants in the Bakken are of earliest Mississippian age. Other evidence supports an earliest Mississippian age for unit 2: the brachiopod fauna of unit 1 suggests that these plants overlie rocks of latest Devonian age and the brachiopod fauna of unit 3 suggests that unit 2 underlies rocks of early, but not earliest, Mississippian age. Also, unit 2 appears to be a transgressive bed and the Early Mississippian "was a time of widespread marine transgressions for North America as well as the rest of the world" (Brezinski, 1986, p. 870). The Uppermost Devonian, by contrast, was a time of worldwide regressions (Sandberg et al, 1983).

Plate 2. Fossils from units 2 and 3, and the upper shale member of the Bakken Formation in North Dakota. 1) Woody plant fragment, upper shale member, 8177, 4347. 2) *Spirifer greenockensis*, pedicle valve, unit 3, 4958, 2775. 3) *Syringothyris halli*, articulated interarea in the upper part of the photo, and a fragment of a brachial valve in the lower part, unit 3, 4958, 2773. 4) *Chonetes ornatus*, brachial valve (upper left); *C. gregarius*, brachial valve (lower right), unit 3, 4958, 2750. 5) *Spirifer greenockensis*, brachial valve and interarea, unit 3, 4958, 2776. 6) *Rhytiophora arcuatus*, one brachial valve (in lower half of photo) and several pedicle valves, unit 3, 8069, 2760. 7) *Chonetes gregarius*, interior of brachial valve, unit 3, 4958, 2747. 8) *Cyrtcus (Licestheria)* sp., two nearly articulated valves with the right valve on top, upper shale member, 607, 2794. 9) *Spirifer* sp. Some of the valves may belong to *S. greenockensis*; a fragment of a brachial valve of *Syringothyris halli* occurs above the *Spirifer* in the center of the photo, unit 3, 4958, 2778. 10) Blade-like "leaves", unit 2, 2967, 4345. 11) ? *Allorhynchus acutiplicum*, pedicle valve, unit 3, 607, 2764. 12) ? *A. heteropsis*, unit 3, 8177, 2763.

1 cm
1

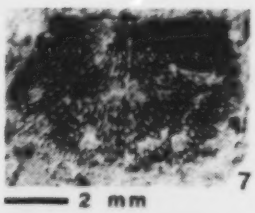
1 cm
2

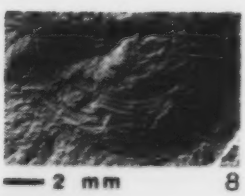
1 cm


2 mm
4

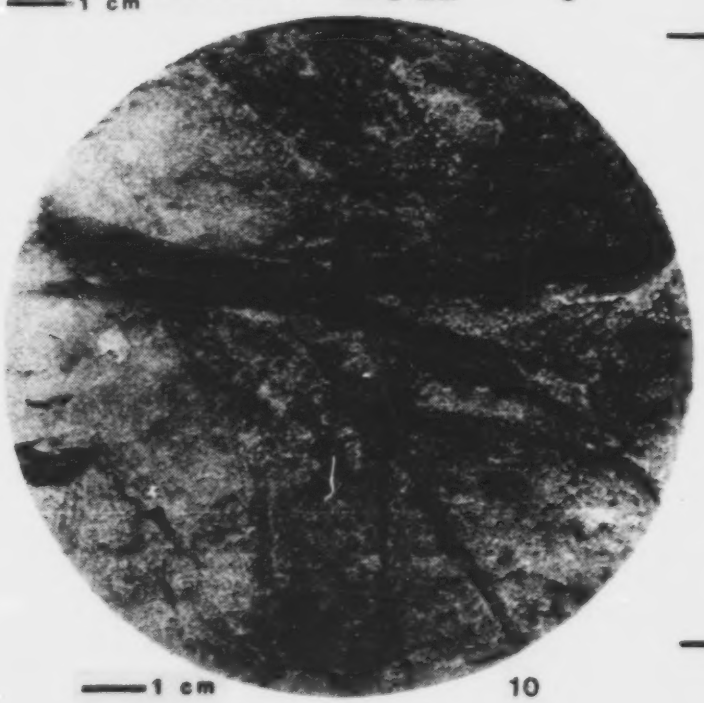
1 cm
5

1 cm
6


2 mm
7


2 mm
8

1 cm
9


1 cm
10

1 cm 11

1 cm
12

The Devonian-Mississippian boundary in North Dakota thus appears to occur in the middle member of the Bakken Formation at the contact between units 1 and 3. This is a poorly defined contact that is commonly transitional over about 5 feet of the section. Evidence of erosion was generally not noted at this juncture, although one core (NDGS 5088) has what appears to be the top of a burrow at the unit 1-unit 2 contact. This core piece (Fig. 11) has poorly preserved fragments of blade-like "leaves" on its upper surface and fragments of calcitic brachiopods on the lower surface.

Fig. 11 Slab photo of the contact between units 1 and 2 of the Bakken Formation (NDGS 5088 at 10,208').

Unit 3 of the middle member occupies the top three to eight feet of the member. It consists predominantly of a massive, medium-gray, fossiliferous siltstone that appears to be lithologically similar to unit 1 but contains more well defined bedding. These beds are most common in the lower one-half of the unit and, other than being fossiliferous, are similar to the thin beds of unit 2. The basal contact of unit 3 is therefore, apparently transitional from the thin beds of unit 2. In some cores, well defined bedding extends upward through most of unit 3 (i.e. to near the top of the middle member); here, the contact between units 2 and 3 was picked just below the lowest occurrence of fossils.

The fossils of unit 3 comprise a brachiopod fauna that appears to differ from the *Syringothyris* fauna of unit 1. The fauna of unit 3 differs most conspicuously from that of unit 1 by containing, often in abundance, *Chonetes gregarious* (Pl. 2, Figs. 4, 7), *C. ornatus* (Pl. 2, Fig. 4) *Syringothyris halli* (Pl. 2, Fig. 3) *Spirifer greenockensis* (Pl. 2, Figs. 2, 5), and *Spirifer* sp. (Pl. 2, Fig. 9), and by lacking some of the distinctive species of unit 1, such as *Tylothyris clarksvillensis* and *Syringothyris hannibalensis*. Also, rhynchonellids are much more common in unit 3 than in unit 1 and *Rhipidomella missouriensis* is much rarer in unit 3 than in unit 1. Other brachiopods that occur in both units 1 and 3 are *Lingula* sp. 4, *Orbiculoidea limata*, *Orbinaria pyxidata*, and *Rhytiophora arcuatus*. In general the faunas are quite similar, as the five species common to both units 1 and 3 represent one-half of the ten taxa found in unit 1. Other brachiopods from unit 3 are *Rugosochonetes* sp., *Composita* spp. 1 and 2, and *Torynifer* sp. The nonbrachiopod fauna of unit 3 is less abundant and less diverse than that of unit 1, consisting of one pelecypod valve, one minute pygidium of *Brachymetopus (Brachymetopus)* sp., one possible pleuron of a trilobite, a few possible arthropod fragments, and rare, disarticulated pelmatozoan columnals. No trace fossils were found in unit 3.

Although most of the brachiopods of unit 3 have been reported to occur in the *Syringothyris* fauna of the Louisiana Limestone or in the Sappington Member and its equivalents, some of the species (such as *Chonetes gregarius* and *Syringothyris halli*) have not previously been reported to occur in rocks older than Early Mississippian (Carter and Carter, 1970).

One formation in which *C. gregarius* occurs with *S. halli* is the McCraney Limestone of Early Mississippian age in the type Mississippian area in southeastern Iowa, northeastern Missouri, and western Illinois. The McCraney is the only formation in the type Mississippian area to have once been considered by many workers to be a part of the Louisiana Limestone. Scott and Collinson (1961, p. 110) wrote, "Few Paleozoic formations have in recent years been subject to more disagreement concerning their age and correlation than have the Louisiana and McCraney Limestones . . . ". The two formations were confused because of their similarity in lithology and fossils, and because, "Even though the two formations occur in the same general area, they have never been positively identified in the same section, either surface or subsurface" (Scott and Collinson, 1961, p. 110). Using conodont evidence, Scott and Collinson (1961) resolved this controversy by demonstrating that the McCraney is of early, but not earliest, Mississippian age and the Louisiana is of latest Devonian age.

The similarity of the faunas of unit 3 and the McCraney Formation to the *Syringothyris* fauna of the Louisiana Limestone is significant in that the Louisiana fauna has been described as being distinctive with few of its taxa occurring independently of the assemblage (Williams, 1943). Because of this similarity, because unit 3 of the Bakken contains species from both the Louisiana and the McCraney, and because unit 3 overlies the *Syringothyris* fauna of unit 1, the fauna of unit 3 seems to be related to the McCraney fauna and is thus considered here to be of nearly the same age as the McCraney Limestone. Other brachiopods in unit 3 support such a correlation. *Chonetes ornatus* is a common species in the McCraney (Stainbrook, 1950), and the rhynchonellids of unit 3 closely resemble *Allorhynchus heteropsis* from the McCraney Limestone.

The history of the *Spirifer marionensis* fauna of the Exshaw Formation is very similar to that of the McCraney fauna. The two faunas were correlated with the distinctive *Syringothyris* fauna of the Louisiana Limestone until conodont evidence found in the 1960s demonstrated that both are of early, but not earliest, Mississippian age and are thus significantly younger than the Louisiana. Both the Exshaw and McCraney contain *Siphonodella cooperi*, which does not occur in rocks older than the Upper *Siphonodella duplicata* Biozone of Early Mississippian age. Direct correlation between these two formations has apparently never been made, but is indicated by this study. Besides containing brachiopods similar to those of the McCraney Limestone, the brachiopods of unit 3, and their stratigraphic position, suggest that this unit should be correlated with the *Spirifer marionensis* Biozone of the Exshaw Formation.

The fossils of the Exshaw siltstone were described as rare and poorly preserved by Macqueen and Sandberg (1970), and Harker and McLaren (1958, p. 251) stated that brachiopods of the Exshaw are not specifically identifiable. Warren (1937, p. 456), however, listed eight species from the Exshaw siltstone, all similar to those found in unit 3 of the Bakken. He listed three species of *Spirifer*, two of which were reported by Brown

(1952) as being similar to *S. greenockensis*. The third, *S. centronatus*, resembles forms assigned here to *Spirifer* sp.. Warren's faunal list also included *Orbinaria concentrica* and *Composita humilis*; these may be conspecific with, respectively, *Orbinaria pyxidata* and *Composita* sp. 2 from the Bakken. The rhynchonellids of unit 3 generally appear similar to three species of rhynchonellids listed by Warren (1937).

The middle member of the Bakken Formation thus appears to contain correlatives of, firstly, the *Syringothyris* fauna of the Louisiana Limestone, the Sappington Member, the Leatham Formation, and the Leatham Member; and secondly, the *Spirifer marionensis* fauna of the Exshaw Formation, itself correlatable with the McCraney Limestone. If true, this is the first occurrence of these two faunas to be recognized together in the same stratigraphic section. It may also be the first finding of two distinct brachiopod biozones in a siltstone member that occurs between two Devonian-Mississippian black shales. The vertical succession of these faunas in the Bakken appears to provide further evidence that the *S. marionensis* fauna of the Exshaw is distinctly younger than the *Syringothyris* fauna of the Sappington Member and its equivalents.

UPPER BAKKEN SHALE

The upper shale member of the Bakken Formation consists of sparsely fossiliferous, dark-gray to black, finely laminated shale nearly identical to the lower shale member. Although macrofossils were found to be relatively common over a short interval in a few of the cores (especially in the upper one-half of the member), no laterally persistent fossiliferous intervals or age-diagnostic fossils were found in this member. Macrofossils of the upper shale member consist of *Orbiculoidea* sp., one indeterminate gastropod, *Cyzicus (Lioestheria)* sp. (Pl. 2, Fig. 1). Also, one bedding plane in the basal few inches of the member contains two disarticulated valves of *Rhipidomella missouriensis*; there is evidence, however, that these valves were reworked from the middle member.

The presence of *Cyzicus (Lioestheria)* sp. in the upper shale member provides further evidence that the range of this conchostracan extends well into the Mississippian. The only fossil found in the upper shale that may relate to a previously established biozone is the woody plant fragment. This specimen, which is too fragmental for generic identification, was found about five feet from the top of the Bakken and may belong to one of more than 25 genera of terrestrial plants that were reported by Cross and Hoskins (1951) to occur within the top few feet of the lower Mississippian black shale units in the eastern interior region, such as the Sunbury and Sanderson Shales.

DISCUSSION

Ettensohn and Barron (1981, p. 354) suggested that the black-shale seas became deep enough for upwelling to occur locally along the coasts of the craton. Evidence they cited for this include beds of radiolarian chert and green shale and concretions of phosphate in the eastern black shales. Such rocks have also been reported from the Late Devonian black shales that crop out in the western interior (Gutschick and Rodriguez, 1979, p. 44) but none was found in this study. Their absence in the Bakken suggests that conditions which caused upwelling along the western margins of the craton did not extend into the eastern portion of the intracratonic sea.

Most workers (e.g. Fuller, 1956; Kume, 1961; Webster, 1982; and Hayes, 1984) have considered the middle member of the Bakken to be a single, homogeneous bed. The only other worker, apparently, to have developed stratigraphic subdivisions for this member is Christopher (1961, 1962) who, on the basis of lithology, divided the middle member in Saskatchewan into an A bed overlain by a B bed. He subdivided his B bed into four interfingering units designated, in ascending order, the B1, B2, and B3 and B4 beds. Judging from his descriptions of the beds, the units proposed here for the middle member are a slightly different way of subdividing comparable rocks. Unit 1 seems to correspond exactly to his A bed, unit 2 to his B1, B2, and B3 beds, and unit 3 to his B4 bed. The thick, cross-bedded, calcareous sandstone or sandy limestone seen on well logs in this study appears similar to his B2 bed which separates his B1 and B3 beds, both similar to the thin-bedded clastics of the rest of unit 2. His system was not used here because the thick sandy bed (his B2 unit) is commonly absent in the cores of this study. Consequently, in many areas of North Dakota, his B1 bed is indistinguishable from his B3 bed. Also, because of the generally massive structure and especially because of the abundance of fossils in the uppermost beds of the middle member, it was felt that these beds should be treated as a separate stratigraphic unit (unit 3) rather than as a subdivision (B4) of the underlying sequence of generally thin-bedded, unfossiliferous rocks that are here assigned to unit 2.

Sandberg et al (1983, p. 707) reported that an eustatic drop in sea level during latest Devonian time resulted in a westward regression of the seas in the western interior. Evidence they cited for this regression in the western United States a westward offset of the *Syringothyris*-bearing siltstone beds from the underlying black shale members and, second, "the shallow-water biota, ichnofossils, and lithologic character of the upper parts of the Sappington Member, the Leatham Formation, and the Leatham Member of the Pilot Shale". Although the middle member of the Bakken has long been associated with this regression because of its correlation with the Louisiana fauna, no other evidence for such a regression has been found in the Bakken. In fact, the middle member is generally considered to be a transgressive, onlapping deposit (Webster, 1982). The division of this member into units 1, 2, and 3 resolves this enigma, however, since the *Syringothyris* fauna was seem only in unit 2, the least extensive unit of the Bakken Formation in North Dakota (Fig. 12). Unlike units 2 and 3, unit 1 was not found to overlap the lower shale member and was the only unit of the Bakken not found in the cores from near the margins of the formation. Unit 1 thus appears to be a regressive deposit that represents the low stand of the Bakken seas. Christopher's subdivision of the middle member

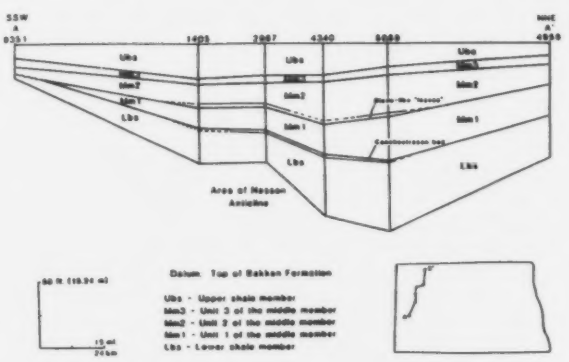


Fig. 12 Stratigraphic cross-section of the Bakken Formation. Well numbers are those of the North Dakota Geological Survey.

also seems to show this regression, as he indicated (1961, Fig. 19, Pl. 5) that his "A bed" is the least extensive stratigraphic unit of the Bakken in Saskatchewan.

Gerhard et al (1982, p. 996) suggested that sometime near the Devonian-Mississippian boundary, a shifting of the alignment of the seaway occurred in the Williston Basin, causing the Mississippian rocks to have a different, more widespread pattern of deposition with a more poorly defined depocenter than in the underlying rocks of the basin. This realignment seems to become first evident in unit 3 of the middle member, as unit 3 and the upper shale member have ill-defined depocenters, are the most widespread beds of the formation, and, aside from regional trends, seem to thicken and thin independently of the rest of the formation. This structural relationship is apparent in the cross-section of the formation (Fig. 12) where, the lower Bakken shale and units 1 and 2 of the middle member are seem to thin out over the Nesson Anticline, whereas the thickness of unit 3 and of the upper Bakken shale appear to be unaffected.

No evidence was seen in this study, or in the studies by Hayes (1984) and Huber (1986), of time transgression of the Bakken units. Regional evidence also indicates nearly isochronous deposition of each of the separate Bakken units. A few workers (e.g. Lineback and Davidson, 1982), however, have suggested that the middle member of the Bakken grades into the subjacent Three Forks Formation near the margins of the basin. Whereas the Bakken has been reported to grade into rocks that resemble the Three Forks near the margins (Fuller, 1956; Christopher, 1961), none of these workers suggested that the Bakken grades into the Three Forks Formation. No evidence for an isochronous age between the Three Forks and Bakken, such as an intermingling of the faunas, was seen in this study. Characteristic fossils of unit 3, such as the chonetids and *Spirifer* sp., were found about 10 feet above the generally fossiliferous beds of the Three Forks Formation in the cores from near the margins of the formation (NDGS 105, 7579, 7887, 8474, and 9351); thus the faunas of the Bakken and the *Cyrtospirifer* brachiopod fauna of the Three Forks Formation appear to remain vertically separated toward the margins of the basin.

ACKNOWLEDGEMENTS

This paper is the result of a Master of Science thesis done at the University of North Dakota in Grand Forks. Thanks go to my adviser, Dr. F. D. Holland, Jr., for his suggestion of the project and for his assistance in all aspects of the study. Thanks are also extended to the other members of my advisory committee, Drs. Alan M. Cvancara and Richard D. LeFever. The North Dakota Geological Survey is gratefully acknowledged for the use of its material and for providing financial assistance for this study. The Dickinson District Office of the U. S. Bureau of Land Mangement is acknowledged for encouraging me to publish this paper. I would also like to thank my colleagues, Linn Gum, Carl Wyant, and Russell Pigors for their constructive criticism of the manuscript.

REFERENCES CITED

Brezinski, D. K., 1986, Trilobite associations from the Chouteau Formation (Kinderhookian) of central Missouri: Journal of Paleontology, v. 60, no. 4, p. 870-881.

Brindle, J. E., 1960, Mississippian megafaunas in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 45, 107 p., 29 pl.

Brown, R. A. C., 1952, Carboniferous stratigraphy and paleontology in the Mt. Greenock area, Alberta: Geological Survey of Canada Memoir 264, 119 p., 5 pl.

Carter, J. L., and Carter, R. C., 1970, Bibliography and index of North American Carboniferous brachiopods (1898-1968): Geological Society of America Memoir 128, 382 p.

Christopher, J. E., 1961, Transitional Devonian-Mississippian formations of southern Saskatchewan: Saskatchewan Department of Mineral Resources Report 66, 103 p., 4 pl.

Christopher, J. E., 1962, The Three Forks Group (Upper Devonian-Kinderhookian) of southern Saskatchewan: 13th Annual Field Conference Guidebook, Billings Geological Society, p. 67-77.

Conkin, J. E., and Conkin, B. M., 1973, The paracontinuity and the determination of the Devonian-Mississippian boundary in the type Lower Mississippian area of North America: University of Louisville Studies in Paleontology and Stratigraphy No. 1, 34 p., 1 pl.

Conkin, J. E., Conkin, B. M., and Lipchinsky, L. Z., 1980, Devonian black shale in the eastern United States: Part I - southern Indiana, Kentucky, northern and eastern Highland Rim of Tennessee, and central Ohio: University of Louisville Studies in Paleontology and Stratigraphy No. 12, 63 p.

Cross, A. T., 1982, Plant macrofossils of the Devonian-Mississippian black shales, eastern interior, U.S.A., a review: Conference on Sedimentology and Paleontology of mid-Continent Black Shales, (unpublished abstract), Cleveland, Ohio.

Cross, A. T., and Hoskins, J. H., 1951, Paleobotany of the Devonian-Mississippian black shales: Journal of Paleontology, v. 25, no. 6, p. 713-728.

Ettensohn, F. R., and Barron, L. S., 1981, Depositional model for the Devonian-Mississippian black shales of North America: A paleoclimatic-paleogeographic approach. In: Roberts, T. G. ed., Geological Society of America Cincinnati '81, Field Trip Guidebooks, Volume 2: Economic geology, structure: American Geological Institute, Washington, D.C., p. 344-361.

Fuller, J. G. C. M., 1956, Mississippian rocks and oilfields in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 19, 51 p.

Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C. G., 1982, Geological development, origin, and energy mineral resources of Williston Basin, North Dakota: American Association of Petroleum Geologists Bulletin, v. 66, no. 8, p. 989-1020.

Gutschick, R. C., and Moreman, W. L., 1967, Devonian-Mississippian boundary relations along the cratonic margin of the U.S. In: Oswald, D. H. ed., International Symposium on the Devonian System, Calgary, Alberta: Alberta Society of Petroleum Geologists, v. 2, p. 1009-1023.

Gutschick, R. C., and Rodriguez, J., 1967, Brachiopod zonation and correlation of the Sappington Formation of western Montana: American Association of Petroleum Geologists Bulletin, v. 51, no. 4, p. 601-620.

Gutschick, R. C., and Rodriguez, J., 1977, Late Devonian-Early Mississippian trace fossils and environments along the Cordilleran miogeosyncline, western U.S. In: Crimes, T. P., and Harper, J. C. eds., Trace Fossils 2: Geological Journal Special Issue 9, Seel House Press, Liverpool, p. 195-208.

Gutschick, R. C., and Rodriguez, J., 1979, Biostratigraphy of the Pilot Shale (Devonian-Mississippian) and contemporaneous strata in Utah, Nevada, and Montana: Brigham Young University Geological Studies, v. 26, pt. 1, p. 37-63.

Harker, P., and McLaren, D. J., 1958, The Devonian-Mississippian boundary in the Alberta Rocky Mountains. In: Goodman, A. J. ed., Jurassic and Carboniferous of Western Canada: American Association of Petroleum Geologists, John A. Allen Memorial Volume, p. 244-253.

Harker, P., and Raasch, G. O., 1958, Megafaunal zones in the Alberta Mississippian and Permian. In: Goodman, A. J., ed., Jurassic and Carboniferous of Western Canada: American Association of Petroleum Geologists, John A. Allen Memorial Volume, p. 216-231.

Hayes, M. D., 1984, Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota: unpublished Mc.Sc. thesis, University of North Dakota, Grand Forks, 178 p., 3 pl.

Hayes, M. D., 1985, Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota: The Mountain Geologist, v. 22, no. 2, p. 64-77, 3 pl.

Huber, T. P., 1986, Conodont biostratigraphy of the Bakken and lower Lodgepole Formations (Devonian and Mississippian), Williston Basin, North Dakota: unpublished M. Sc. thesis, University of North Dakota, Grand Forks, 274 p.

Klapper, G., 1966, Upper Devonian and Lower Mississippian conodont zones in Montana, Wyoming, and South Dakota: The University of Kansas Paleontological Contributions, Paper 3, 43 p.

Kume, J., 1963, The Bakken and Englewood Formations of North Dakota and northwestern South Dakota: North Dakota Geological Survey Bulletin 39, 87 p.

Lineback, J. A., and Davidson, M. L., 1982, The Williston Basin — sediment-starved during the Early Mississippian. In: Kaldi, J., and Christopher, J. E. eds., Fourth International Williston Basin Symposium, Saskatchewan Geological Society and North Dakota Geological Society: Saskatchewan Geological Society Special Publications No. 6, p. 125-130.

Macqueen, R. W., and Sandberg, C. A., 1970, Stratigraphy, age, and interregional correlation of the Exshaw Formation, Alberta Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, no. 1, p. 32-66.

Mathews, R. D., 1983, *Foerstia* from the Antrim Shale (Devonian) of Michigan: Geology, v. 11, no. 6, p. 327-330.

Meissner, F. F., 1978, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana: Williston Basin Symposium, 24th Annual Field Conference Guidebook, Montana Geological Society, p. 207-231.

Mitchell, J. G., and Maher, J. C., 1957, Suggested abbreviations for lithologic descriptions: American Association of Petroleum Geologists Bulletin, v. 41, no. 9, p. 2103-2107.

Penner, D. G., 1958, Mississippian stratigraphy of the southern Alberta Plains. In; Goodman, A. J. ed., Jurassic and Carboniferous of Western Canada: American Association of Petroleum Geologists, John Andrew Allen Memorial Volume, p. 260-288.

Rodriguez, J., and Gutschick, R. C., 1975, Epibiontic relationships on a Late Devonian algal bank: Journal of Paleontology, v. 49, no. 6, p. 1112-1120, 5 text figs.

Russel, D. J., 1985, Depositional analysis of a black shale by using gamma ray stratigraphy: the Upper Devonian Kettle Point Formation of Ontario: Bulletin of Canadian Petroleum Geology, v. 33, no. 6, p. 236-253.

Sandberg, C. A., 1979, Devonian and Lower Mississippian conodont zonation of the Great Basin and Rocky Mountains. In: Sandberg, C. A., and Clark, D. L. eds., Conodont biostratigraphy of the Great Basin and Rocky Mountains: Brigham Young University Geology Studies, v. 26, pt. 3, p. 87-106.

Sandberg, C. A., and Gutschick, R. C., 1979, Guide to conodont biostratigraphy of Upper Devonian and Mississippian rocks along the Wasatch Front and Cordilleran Hingeline, Utah. In: Sandberg, C. A., and Clark. D. L., eds., Conodont Biostratigraphy of the Great Basin and the Rocky Mountains: Brigham Young University Geology Studies, v. 26, pt. 3, p. 107-133.

Sandberg, C. A., Gutschick, R. C., Johnson, J. G., Poole, F. G., and Sando, W. J., 1983, Middle Devonian to Late Mississippian geological history of the Overthrust Belt region, western United States: Rocky Mountain Association of Geologists, Geologic Studies of the Cordilleran Thrust Belt, v. 2, p. 691-719.

Sandberg, C. A., and Klapper, G., 1967, Stratigraphy, age, and paleotectonic significance of the Cottonwood Canyon Member of the Madison Limestone in Wyoming and Montana: U. S. Geological Survey Bulletin 1251-B, p. B1-B70.

Sandberg, C. A., and Mapel, W. J., 1967, The Devonian of the northern Rocky Mountains and plains. In: Oswald, D. H., ed., International Symposium on the Devonian System, Volume I: Alberta Society of Petroleum Geologists, p. 843-877.

Sandberg, C. A., and Poole, F. G., 1977, Conodont biostratigraphy and depositional complexes of the Upper Devonian cratonic platform and continental shelf rocks in the western U.S. In: Murphy, M. A., Berry, W. B. N., and Sandberg, C. A., eds., Western North America: Devonian: University of California, Riverside, Museum Contributions no. 4, p. 144-180.

Sandberg, C. A., Poole, F. G., and Gutschick, R. C., 1980, Devonian and Mississippian stratigraphy and conodont zonation of the Pilot and Chainman Shales, Confusion Range, Utah. In: Fouch, T. D., and Magathan, E. R. eds., Paleozoic paleogeography of

west-central U.S.: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Paleogeography Symposium 1, p. 71-79.

Sandberg, C. A., Streel, M., and Scott, R. A., 1972, Comparison between conodont zonation and spore assemblages at the Devonian-Carboniferous boundary in the western and central U.S. and Europe: 7th International Congress for Stratigraphy and Geology of the Carboniferous, Krefeld, v. 1, p. 179-203, 4 pl.

Sartenaer, P., 1967, Famennian Rhynchonellid brachiopod genera as a tool for correlation. In: Oswald, D. H. ed., International Symposium on the Devonian System, Calgary, Alberta: Canadian Association of Petroleum Geologists, v. 2, p. 1043-1060.

Scott, A. J., and Collinson, C. W., 1961, Conodont faunas from the Louisiana and McCraney Formations of Illinois, Iowa, and Missouri: Kansas Geological Society Guidebook, 26th Annual Field Conference, northeastern Missouri and west-central Illinois, p. 100-109.

Stainbrook, M. A., 1950, The fauna and correlation of the McCraney Limestone of Iowa and Illinois: American Journal of Science, v. 248, p. 194-213.

Warren, P. S., 1937, Age of the Exshaw Shale in the Canadian Rockies: American Journal of Science, ser. 5, v. 33, p. 454-457.

Webster, R. L., 1982, Analysis of petroleum source rocks of the Bakken Formation (Devonian-Mississippian) in North Dakota: unpublished M. Sc. thesis, University of North Dakota, Grand Forks, 150 p.

Williams, J. S., 1943, Stratigraphy and fauna of the Louisiana Limestone of Missouri: U. S. Geological Survey Professional Paper 203, 133 p., 4 pl.

Ziegler, W., and Sandberg, C. A., 1984, *Palmatolepis*-based revision of upper part of standard Late Devonian conodont zonation. In: Clark, D. L., ed., Conodont Biofacies and Provincialism: Geological Society of America, Special Paper 196, p. 179-194.

SUMMARY OF THE BIOSTRATIGRAPHY OF THE BAKKEN FORMATION (DEVONIAN AND MISSISSIPPIAN) IN THE WILLISTON BASIN, NORTH DAKOTA

F.D. HOLLAND, JR., M. D. HAYES[1], L. C. THRASHER[2] AND T. P. HUBER[3]

Department of Geology and Geological Engineering
University of North Dakota
Grand Forks, ND 58202

ABSTRACT

Few fossils have been collected from the Bakken Formation in North Dakota until recent years. Originally described as Mississippian, the Bakken has been correlated by lithology and well logs with both Devonian and Mississippian outcropping units in nearby states and provinces. Studies of 95 form-species (assigned to 22 form-genera) of conodonts and more than 500 macrofossils in 50 taxa from 30 cores now allow more accurate Bakken biozonation in North Dakota. The Bakken, up to 45 metres thick, is as old as the Late Famennian Lower *Palmatolepis gracilis expansa* Biozone and as young as the Kinderhookian Lower *Siphonodella crenulata* Biozone. A lower, black-shale member, less than 16 m thick, has a brachiopod fauna in the bottom metre, conodonts perhaps as old as the Lower *Palmatolepis perlobata postera* Biozone, the alga *Foerstia* 2 m above the base, and abundant conchostracans marking the top. A middle member, lacking age-diagnostic conodonts, has been divided into three lithologic units: a lower, massive, gray, 9 m siltstone unit with a Late Famennian brachiopod fauna; a middle unit (3-11 m thick) of thin, largely unfossiliferous laminae of gray mudstone and siltstone with "blade-like leaves" near the base; and an upper, massive, gray siltstone, less than 3 m thick, with a distinctly Mississippian *Spirifer s. s.* fauna. The systemic boundary has been placed at the base of the second unit of the middle member. An upper black-shale member, less than 7.5 m thick, contains *Siphonodella sulcata* at the base, rare macrofossils, and perhaps as many as three Kinderhookian conodont biozones. Deposition of the upper member of the Bakken may have begun as early as the time of the late Upper *S. duplicata* Biozone and continued through the *S. sandbergi* Biozone into the Lower *S. crenulata* Biozone; although, more likely, deposition of the upper member began in the time of the Lower *Siphonodella crenulata* Biozone. This biozone is represented in both the upper member of the Bakken and the lower part of the Lodgepole Formation. Above this, suggestion of the *S. isosticha*—Upper *S. crenulata* Biozone was found in the Lodgepole; but conodont numbers dwindled rapidly to disappearance by 15 metres above the base of the Lodgepole, before the Kinderhookian-Osagean boundary was reached.

INTRODUCTION

For many years after Nordquist (1953, p. 72) named the Bakken Formation, from the Amerada Petroleum Corp.-H. O. Bakken No. 1 well (NDGS Well No. 32) in Williams County, North Dakota, the age of the formation was given as Early Mississippian. As late as 1984, workers (e.g. Leenheer, 1984) have cited the Bakken as of Mississippian age even though Sandberg and Hammond (1958, p. 2326, 2328) had suggested that the Bakken is not entirely Mississippian age, Klapper (1966) had created an Upper Devonian and Lower Mississippian biozonation for Bakken correlatives in neighbouring states, and Sandberg and Klapper (1967, p. B37-B39) and Sandberg and Mapel (1967, p. 872) had discussed the Late Devonian-Early Mississippian age of the Bakken and its correlatives. The reluctance of workers to accept placement of the Devonian-Mississippian boundary within the Bakken Formation is understandable because, until recently, precious few fossils have been obtained from the Bakken Formation within the Williston Basin in North Dakota. Kume (1960, 1963) had reported a few specimens from North Dakota but most paleontological evidence for the age of the Bakken has come from outside the state. Thus the age of the Bakken in North Dakota has rested on lithostratigraphic correlations. In Saskatchewan, Brindle (1960, p. 16) had "confidently ascribed" a Mississippian age to brachiopods he had recovered from Bakken cores although Christoper (1961, p. 19) placed the systemic boundary at the base of the "Middle sandstone" within the Bakken based on physical evidence and correction of a typographical error in Brindle's paleontological evidence. Thus, only after a program of detailed studies of the Bakken (Webster, 1982, 1984) was initiated in 1979 at the University of North Dakota have enough fossils been found in the Bakken in North Dakota to enable us to give a relatively complete picture of Bakken biostratigraphy within the State. This paper seeks to summarize the results of these biostratigraphic studies.

Several things have led to the success of our efforts: (1) the development of a technique to extract conodonts from dark gray to black, carbonaceous clay shale by oxidation of the organic matter binding the clay minerals of the shale (Duffield and Warshauer, 1979); (2) acquisition of an adequate amount of core from the Bakken Formation so that the North Dakota Geological Survey could allow, with equanimity, destroying even a thin piece of core, during processing by oxidation or acidizing, for extraction of microfossils; (3) development of a world-wide, conodont, biozonation scheme for this part of the column by Zeigler (1962), Sandberg (1979), Lane, Sandberg, and Ziegler (1980), and recently refined by Ziegler and Sandberg (1984); (4) successful oxidation of the dark Bakken shales by Hayes (1984; 1985) and refinement of these results by Huber (1986); and (5) the finding by Thrasher (1985; and this volume) of numerous macrofossils in the middle, siltstone member of the Bakken.

REGIONAL STRATIGRAPHIC BACKGROUND

One does not have to search long nor hard to find reason and justification for studying the Bakken Formation. Its importance is well known; it may be best known as the premier marker in the Basin because it is such a distinctive formation—two dark gray to black, radioactive, shale members easily recognized in cores, cutting, or gamma-ray logs (by the off-scale readings)—enclosing (where all members are present) a fine-grained siliciclastic member that shows up as a more "normal" log signature. Also, the Bakken is widely considered a source of the petroleum of the prolific reservoirs in the Madison Group that everywhere overlies the Bakken (Murray, 1968; Williams, 1974; Dow, 1974; Meissner, 1978; Thode,

Present address: [1]Exxon, U.S.A., Midland, Texas 79714; [2]Bureau of Land Management, Dickinson, North Dakota 58602; [3]France Avenue South, Minneapolis, Minnesota 55410.

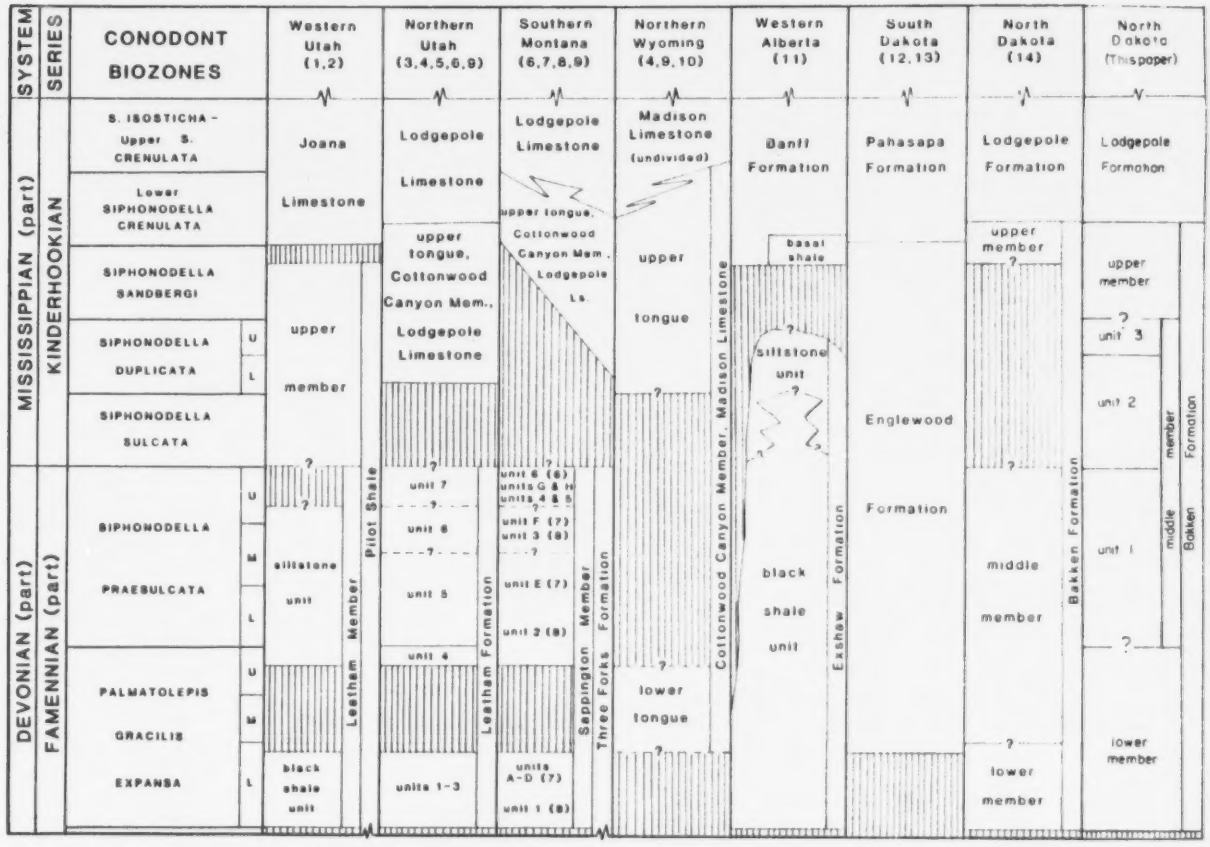


Fig. 1 Correlation of the Bakken Formation with other units in its depositional complex in the Western Interior (modified from Huber, 1986, p. 27). Conodont biozones are from Sandberg (1979) and Ziegler and Sandberg (1984); biozone abbreviations L, M, and U are Lower, Middle, and Upper, respectively. Break lines at top and bottom of columns indicate that the unit involved extends above or below this figure. Sources of information for each column correspond to numbers enclosed in parentheses as follows: (1) Gutschick and Rodriguez (1979); (2) Sandberg et al (1980); (3) Sandberg and Gutschick (1969); (4) Sandberg and Poole (1977); (5) Sandberg and Gutschick (1979); (6) Sandberg et al (1972); (7) Gutschick et al (1962); (8) Sandberg (1965); (9) Sandberg and Klapper (1967); (10) Sando (1967); (11) Macqueen and Sandberg (1970); (12) Klapper and Furnish (1962); (13) Klapper (1966); (14) Hayes (1985).

1981; Krystinik and Charpentier, 1984; Price et al, 1984; Dembicki and Pirkle, 1985; Spencer, 1987); and lastly the Bakken is receiving increasing attention for its reservoir properties (e.g. preceeding references, and Wilson, 1983; Hester and Schmoker, 1983; Schmoker and Hester, 1983; Cramer, 1986). However, the significance of the Bakken's geochronology, environments of deposition, and depositional history are not so well known and have yet to be appreciated.

The general stratigraphic position of the Bakken Formation, regardless of its geochronologic age, is also well known—everywhere underlain by the Three Forks Formation and overlain by the Lodgepole Formation. For more than two decades, the Bakken has been recognized as part of a vast depositional complex (Sandberg and Mapel, 1967; Sandberg and Poole, 1977) of closely related units (Fig. 1) stretching, in the Western Interior, from the Leatham Member of the Pilot Shale in Nevada through the Leatham Formation of northeastern Utah, the Sappington Member of the Three Forks Formation in Montana, the Cottonwood Canyon Member of the Lodgepole Formation in Wyoming (or of the Madison Formation in northeastern Wyoming where separate formations of the Madison cannot be recognized) to the Englewood Formation in South Dakota (Klapper and Furnish, 1962 and Klapper, 1966) and northward into Canada where units of this depositional complex are known as the Exshaw Formation (Macqueen and Sandberg, 1970). The characteristics of this depositional complex are: (1) lithogenetically related clastic units; (2) comparable thicknesses and stratigraphic sequences; (3) largely consisting of a lower, dark, organic-rich shale, overlain by a lighter-colored, middle, calcareous siltstone, and then an upper, dark, organic-rich shale of a character similar to that of the lower shale (except for the Englewood Formation and the Cottonwood Canyon Member of the Lodgepole or Madison Formations in Wyoming at the same approximate stratigraphic level although their lithologies are different); (4) exhibiting generally continuous deposition across the Devonian-Mississippian boundary although there may be local, minor disconformities within the dark shale-light siltstone-dark shale sequence; (5) likely originally depositionally continuous rock bodies; (6) with comparable faunas; and (7) comparable responses to the late Famennian, Antler orogeny in the west.

The fauna of this depositional complex is fairly well known, especially through the work of Raymond C. Gutschick, Joaquin Rodriguez, Charles A. Sandberg and their colleagues, in a whole series of papers (Gutschick, 1962, 1964 [1966]; Gutschick and Moreman, 1967; Gutschick and Perry, 1959; Gutschick, McLane, and Rodriguez, 1976; Gutschick and Rodriguez, 1967, 1977, 1979; Gutschick and Sandberg, 1970, 1983; Gutschick, Suttner, and Switek, 1962; Rodriguez and Gutschick, 1967, 1970, 1975, 1978; Sandberg, 1976; Sandberg and Gutschick, 1979; Sandberg and Klapper, 1967; Sandberg

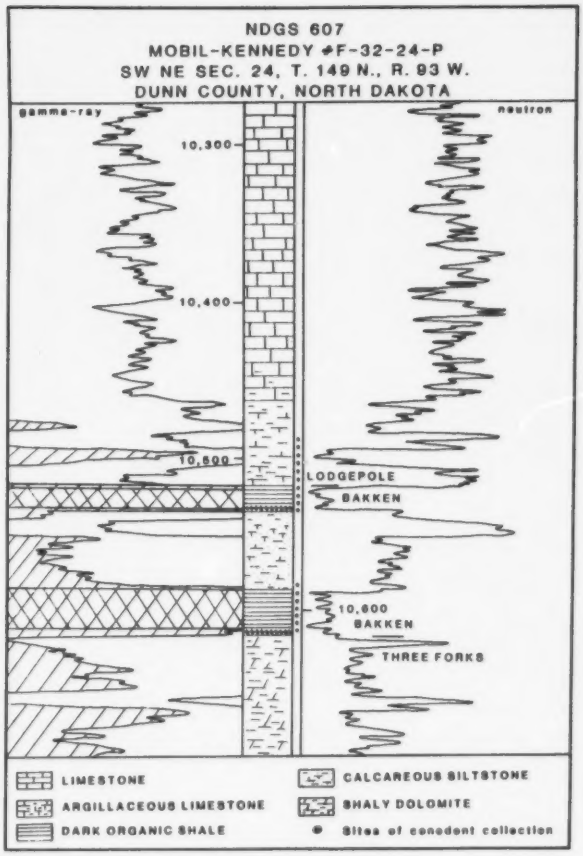


Fig. 2 Gamma ray-neutron log and generalized lithology of the Bakken Formation and adjacent units, showing the levels of conodont collections, in a typical western North Dakota well. Small "L's" indicate the position of conodont concentrates ("lag" zones). From Huber (1986, p. 68).

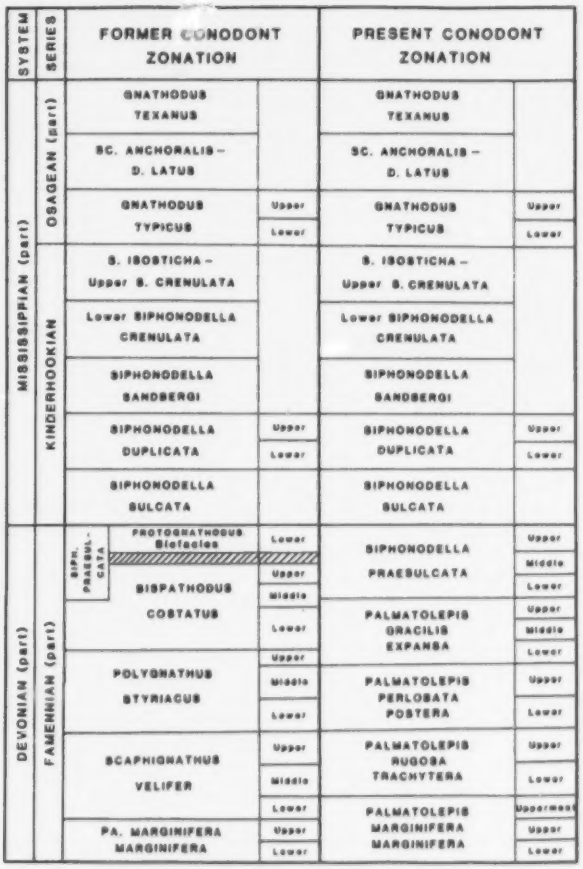


Fig. 3 Conodont biozonation scheme of Upper Devonian and Lower Mississippian rocks: former (Sandberg, 1979) and present (Siegler and Sandberg, 1984; Lane et al, 1980). Ruled area represents an unzoned interval lacking diagnostic conodonts. Form-genera abbreviations: (SC) *Scal. ignathus*, (D.) *Doliognathus*, (S., SIPH.) *Siphonodella*, (PA.) *Palmatolepis*. From Huber (1986, p. 48).

and Mapel, 1967; Sandberg and Poole, 1977; Sandberg, Poole, and Gutschick, 1980; Sandberg, Streel, and Scott, 1972; Sprinkle and Gutschick, 1967); and Achauer (1959), and Alexander (1977).

Many of the beds in the Bakken's depositional complex are not particularly fossiliferous, but some contain abundant macrofossils; macrofossils from the upper part of the lower shales and from the light-colored siltstone units of the complex form widespread biosomes over the northern part of the Western Interior. Whereas macrofossils, particularly brachiopods, ichnofossils, and zones of conchostracans, especially from the siltstones, have aided correlation within this complex and with units outside of the west, it is the conodonts from the black shales (Fig. 2) that have provided the most consistent biostratigraphic calibration of units—precisely from those units where macrofossils are the scarcest. Taken together, five assemblages of macrofossils and the conodonts from the black shales have enabled us to fit the Bakken Formation of North Dakota (Fig. 1) into the world-wide biozonation scheme (Fig. 3.)

METHODS

More than 40 cores, stored in the Wilson M. Laird Core and Sample Library of the North Dakota Geological Survey on the campus of the University of North Dakota, were examined with the aid of a handlens and binocular stereoscope. In the lower 15 metres of the Lodgepole Limestone and the middle member of the Bakken, a rocker slab of core was removed for crushing to about one-half centimeter size, condensed into two to three core-box intervals (1-3 m), divided and then placed in plastic vessels in a fume hood in 8-10 percent acetic acid (Collinson, 1963). From the Bakken black shales, samples were preferentially (although not exclusively) split from core where more than five conodonts were observed on a bedding plane. These samples were further cleaved to increase the surface area, weighed, and covered with a solution of 4-6 percent sodium hypochlorite (household bleach) to oxidize the organic binding material of the dark shale, thereby releasing the conodonts. One hundred grams of sodium hydroxide beads were added to each gallon (4 litres) of bleach to create a strongly basic solution and enhance the oxidation reaction (Duffield and Warshauer, 1979). Water was added to the baths to offset evaporation; and periodically, the samples were cleaned, to remove an argillaceous coating that enveloped the fragments, by thoroughly washing the samples with tap water on a nested set of -0.25 phi and 3.75 phi U.S. Standard sieves. The average processing time for the shale samples was some 10-14 weeks; although samples were not completely disaggregated in this time, commonly some 50 percent of the material had been removed by then. Some conodont-rich zones were left in the bleach and sodium hydroxide solution up to 35 weeks with only 60-70 weight percent of the sample

removed. After washing and drying of the samples, conodonts were picked under the microscope, with a No. 00 sable brush, for removal to micropaleontological slides for identification and storage, as neither the Franz Isodynamic Magnetic Separator (Dow, 1960) nor the method described by Merrill (1985) proved efficacious in concentration or removal of conodonts. Selected specimens were gold-coated and photographed in the JEOL 35C Scanning Electron Microscope/ Electron Probe in the Natural Materials Analytical Laboratory (NMAL) of the Mining and Mineral Resources Research Institute (MMRRI) and the Department of Geology and Geological Engineering.

Macrofossils were collected (Thrasher, 1985) from 26 cores of some interval from the Bakken Formation, mostly the middle member. More than 500 megafossils on about 250 core pieces were found and excavated as needed, using a hammer and small chisels or a sharpened steel probe and a camel-hair brush under a stereoscopic binocular microscope.

BAKKEN BIOSTRATIGRAPHY

LOWER MEMBER

The depocenter of the Bakken Formation is in western Mountrail County, just east of the current Nesson Anticline about 72 km (45 mi.) east of Williston, North Dakota, where the Bakken is up to 45 m (148 ft.) thick in the Kissinger Petroleum Corp.-Grondale No. 1-9 well (NDGS well no. 7570). In this area, the lower member of the Bakken makes up about 33 percent of the thickness of the formation, the middle member about 53 percent, and the upper member approximately 14 percent. The lower member begins abruptly above the Three Forks Formation with a few rip-up clasts (as in the Shell Oil Co.-Burbank BIA No. 23-8 well in Dunn County; NDGS well no. 8709) in the black shale. It carries within the basal couple of metres, a brachiopod fauna (rare but locally abundant) characterized by the rhynchonellide *Rugaltarostrum madisonense* with the inarticulates *Lingula* and *Barroisella* , gastropod *Straparollus*, and abundant clam shrimps, the phyllopod crustacean *Cyzicus (Lioestheria)* sp. Macrofossils are rare through most of this member, but it has produced the conodont form-species *Polygnathodus experplexus* and *Bispathodus jugosus* that have a short range but first appear in the Lower *Palmatolepis gracilis expansa* Biozone, indicating the presence of this biozone (Fig. 3). The presence of *Polygnathus granulosus*, which becomes extinct within this biozone, together with other species commoner in older biozones, suggests the possibility that this member may be as old as the *Palmatolepis perlobata postera* Biozone. This fauna near the base and the rarity of macrofossils and age-diagnostic conodonts up in the black shale suggest a struggling paleocommunity of shallow-water organisms overwhelmed by the onset of anaerobic conditions during the time of early black-shale deposition. Thrasher found excellent specimens of thalli of the pelagic alga *Foerstia (Protosalvinia)* sp. (Matthews, 1983) two metres above the base of the black shale, on both sides of a thin limestone in the Pan American Petroleum Corp.-Clifford Marmon No. 1 well (NDGS well no. 4340) in southeastern Williams County. This occurrence may indicate a slight shoaling of the water or an upwelling or stirring of anoxic waters overcame these floating algae.

The top of the lower member is marked by a conchostracan bed that is widespread in this deeper part of the basin. This occurrence of abundant *Cyzicus (Lioesteria)* sp. at the top of the black shale, below the middle Bakken siltstone, matches in position an occurrence of this species in black shale at the base of a comparable siltstone unit in the Leatham Formation of northeastern Utah and the Leatham Member of the Pilot Shale in Nevada and western Utah. That occurrence of conchostracans was taken by Gutschick and Rodriguez (1979, p. 44) to indicate some of the oldest conchostracans, at the approximate position of the Middle *Bispathodus costatus* zone or at about the base of the Lower *Siphonodella praesulcata* Biozone of the present scheme. Obviously, the occurrence of conchostracans near the base of the lower member in the Williston Basin indicates that these conchostracans were yet older than previously thought, with this species perhaps originating on the craton in this interior-sag type of basin (IS2 basin of Kingston, Dishroon, and Williams, 1983).

MIDDLE MEMBER

Three units seem to be distinguishable (Thrasher, 1985; and this volume) within the middle member (commonly called a siltstone but perhaps more properly, a mudstone). A pycnocline, marking the top of anoxic conditions, did not seem to be developed during the deposition of the middle member, and the water seems to have been oxygenated to the floor of the sea. The lowest unit, unit 1, is a light- to dark-gray, commonly with a greenish cast, bioturbated, fossiliferous siltstone. Whereas the orthid brachiopod, *Rhipidomella missouriensis* dominates this assemblage, the spiriferids *Tylothyris clarksvillensis* and *Syringothyris hannibalensis* are the more age-diagnostic fossils, as they occur in the Late Famennian Louisiana Limestone in Missouri. This assemblage has the ichnospecies *Scalarituba missouriensis* and many other of the elements of the prominent, calcareous siltstone of the Leatham Formation; although it lacks the epibionts and boring ichnofossils of the oncolite bank reported by Gutschick and Rodriguez (1979, p. 46) in the Leatham, suggesting that the water did not get as shallow at this time in the Williston Basin as in the shoal on the edge of the miogeocline in Utah and northward, or that more mud was brought in to dilute the calcium carbonate content in the Williston Basin, or yet, the water was more stirred by storm waves.

Unit 2 of the middle member, up to 11 m (35 ft.) thick, has more distinct bedding with good primary structures and is better sorted than unit 1. Unit 2 contains few fossils except "blade-like leaves", in the basal metre in several wells, comparable to those reported from the type area of the Mississipian in western Illinois in strata at the base of the *Siphonodella sulcata* Biozone (Conkin and Conkin, 1973). This, together with the onlapping of unit 1 by unit 2, is taken as circumstantial evidence of the base of the Mississippian System in the deepest part of the Williston Basin, bracketed as it is by Devonian fossils of unit 1 below and a Mississippian brachiopod fauna of unit 3, above.

The lithology of unit 3, less than 3 m (10 ft.) thick, resembles that of unit 1 except that unit 3 has more well-defined bedding, especially in the bottom half of the unit, than does unit 1. While it lacks the bioturbation and trace fossils of unit 1, it is fossiliferous. Normally of more massive siltstone than unit 2, in some wells the thin laminae of unit 2 carry upward through much of unit 3; in these wells, the base of unit 3 was picked below the lowest occurrence of fossils. Picked on either thickness or lowest fossils, the base of the unit is rather consistently a similar distance above a distinctive, thick, sandy bed in the upper half of unit 2.

Sixteen species of brachipods have been recovered from unit 3. Of these, only two inarticulates and three articulates, *Rhipidomella missouriensis*, *Orbinaria pyxidata*, and *Rhytiophora arcuata*, also occur in unit 1, although the latter two

productelloids are more common in unit 3 while *Rhipidomella* is about 10 to 1 more abundant in unit 1 than in unit 3. The fauna of unit 3 is dominated by *Spirifer* and *Chonetes*, neither of which is found in unit 1. The *Syringothyris* of this unit, *S. halli*, can easily be told from the spiriferids by its non-costate fold and sulcus and it is less than half the size of *S. hannibalensis* from unit 1. This fauna is closely allied with that of the McCraney Limestone, of Mississippian age (Scott and Collinson, 1961; Lane and Sevastopulo, 1986) in Illinois and that of the upper Exshaw Formation of Alberta. In the Bakken Formation, 11 species occur only in units here assigned to the Mississippian. In spite of diligent search, only a few, indeterminate, ramiform conodonts have been recovered from the middle member of the Bakken.

UPPER MEMBER

The upper member of the Bakken, 6-7.5 m (20-25 ft.) thick in the center of the Basin, is a black, finely laminated shale, similar to the black shale of the lower member of the Bakken, that seems to represent a continued transgression with return to anoxic conditions. The only macrofossils that occur in any number (15 specimens) in this unit are the conchostracans,

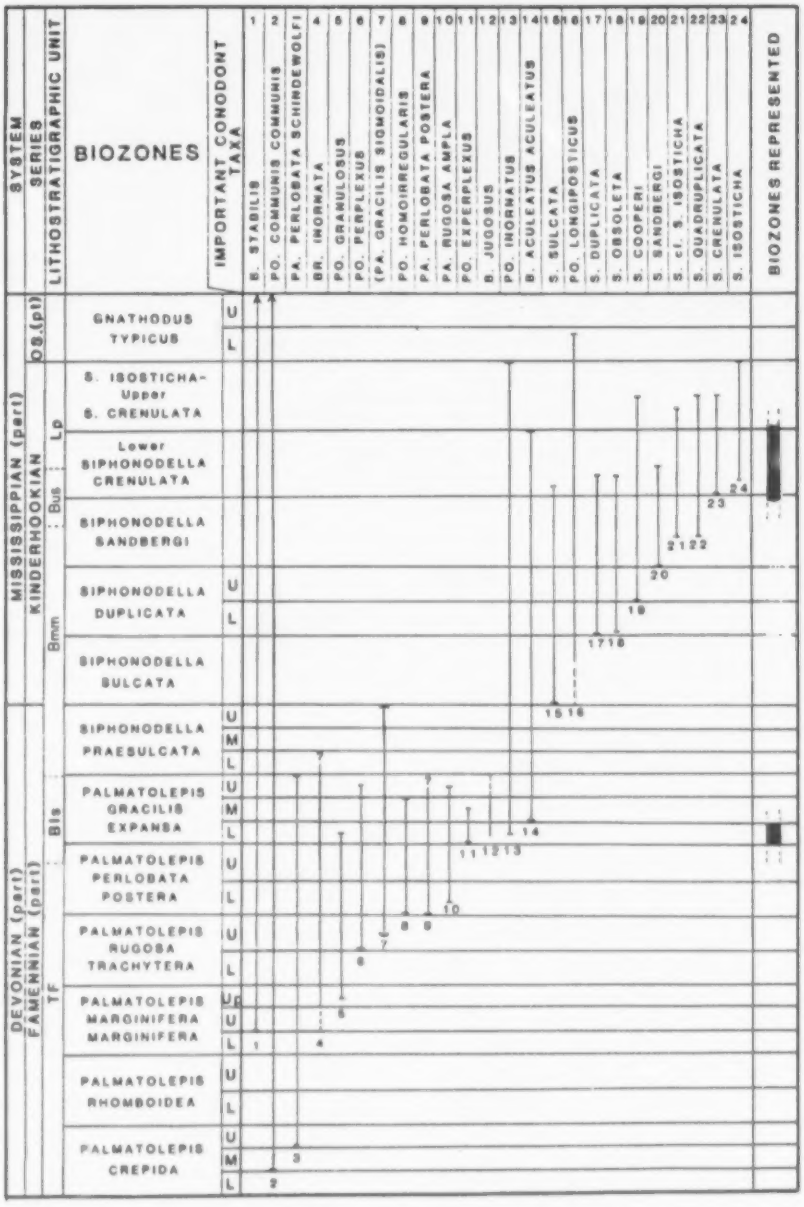


Fig. 4 Previously reported ranges of 24 conodont form-taxa recovered from the Bakken and Lodgepole Formations. *Palmatolepis gracilis sigmoidalis* was collected by Hayes. Sources for the ranges and biozonation are Ziegler (1971), Sandberg (1979), Lane et al (1980), and Ziegler and Sandberg (1984). Taxon abbreviations are: (B.) *Bispathodus*, (Po.) *Polygnathus*, (Pa.) *Palmatolepis*, (Br.) *Branmehla*, and (S.) *Siphonodella*. Unit abbreviations are: (OS) Osagean; (Bis), (Bmm), (Bus),lower, middle, and upper members of the Bakken Formation, respectively; and (Lp) Lodgepole Formation. Modified slightly from Huber (1986, p. 101).

Cyzicus (Lioestheria), sp., at several horizons.

Nearly 1500 conodont elements have been recovered by oxidation of core fragments from the upper member. Aside from long-ranging forms (Fig. 4), such as *Bispathodus stabilis* and *Polygnathus communis communis*, that occur in the lower member as well, the diagnostic platform elements make up one or more of the distinctly Kinderhookian siphonodellid faunas, quite different in aspect from the Devonian faunas, for the Lower Mississippian was a time of speciation within *Siphonodella*. The more important Mississippian forms found in the upper member are: *Siphonodella sulcata, S. duplicata, S. obsoleta, S. cooperi, S. sandbergi, S. quadriduplicata, S. crenulata*, and *Elictognathus laceratus*. Peculiarly, long-ranging forms that occur in Devonian as well as Mississippian rocks elsewhere, have so far been found only in the upper member in North Dakota—*Bispathodus aculeatus aculeatus*, and *Polygnathus inornatus*. Taken together, the conodonts indicate the presence of the Lower *Siphonodella crenulata* Biozone in the upper member as these forms occur together only in that biozone, indicating an early, but not earliest Mississippian age for the upper member. The presence of *S. sandbergi* in the absence of *S. crenulata* (on, however, only one bedding plane) suggests the possibility of the presence of the *Siphonodella sandbergi* Biozone. While the presence of specimens of *S. sulcata* might suggest the presence of earliest Mississippian biozones in the upper member, the occurrence of these specimens of *S. crenulata* and *S. duplicata* in thin zones of conodont concentration ("lag" zones) indicate that, more likely, earliest Mississippian strata, in the Williston Basin, are those of units 2 and 3 of the middle member of the Bakken.

The more than 740 conodont elements reported by Huber (1986) as the result of acidizing the lower part of the Lodgepole Formation are the basis of another paper (Huber and Holland, in prep.) Suffice it to say here that these are mostly forms of the fauna of the upper member of the Bakken, indicating that the Lower *Siphonodella crenulata* Biozone and deposition continued without interruption across the sharp formational boundary into the Lodgepole. The Lodgepole fauna had the addition of *S. isosticha*, numerous *S.* cf *S. isosticha* (Hayes, 1984, reported one specimen from the upper member), *Pseudopolygnathus triangulus*, and two species of *Dinodus*. Whereas all of these are reported elsewhere as beginning in earlier biozones, their lowest yet-known occurrence in North Dakota in the limestone of the Lodgepole (and in the absence of *S. sulcata*) suggests the presence of at least the lower part of the *Siphonodella isosticha* - Upper *Siphonodella crenulata* Biozone in the lower Lodgepole. However, although the base of this biozone is defined by the lowest occurrence of *Gnathodus delicatus*, no gnathodids were found. The highest occurrence of a siphonodellid element was in an interval 9-10.7 m (29-35 ft.) above the top of the Bakken; shortly above this, conodonts became conspicuously absent without reaching the uppermost Kinderhookian biozone or the occurrence of Osagean forms.

"TO DO" LIST

We have been asked, "How many studies, for gosh sakes, on the Bakken?". While we are gratified that we have been able to give general biochronologic dates for the Bakken Formation, we now realize how much we don't know. Much work remains to be done on the Bakken: (a) Detailed petrology (including kind and origin of the pyrite grains) of the two black shales: are they the same lithologically?; (b) Petrology of the units in the middle member and explication of the sedimentary structures; (c) Paleontological evaluation of the Three Forks-Bakken contact and the petrology of the local "Sanish sand" at the top of the Three Forks; (d) Study of the fracture-derived porosity and permeability of the Bakken, especially that so pronounced in the black shales; (e) Foot-by-foot collection of conodonts to support statistical treatment of conodont biozonation; (f) Conodont and macrofossil paleobiogeographic study; (g) Bakken paleopalynology; (h) Further (Webster, 1982, p. 74-94) work on burial history; and (i) Utilization of petrology of members in concentration on the pinchout of Bakken members toward the margins of the Basin (hindered by lack of core) and the relation of the Bakken to the Carrington (North Dakota) and Routledge (Manitoba) black-shale lithofacies of the basal Madison.

SUMMARY OF CONCLUSIONS

An oxidation technique allowed recovery of a conodont fauna containing the form-species *Polygnathus experplexus* and *Bispathodus jugosus*, occurring with the Late Famennian brachiopod *Rugaltarostrum madisonense*, indicating the presence of the Lower *Palmatolepis gracilis epansa* Biozone at the bottom of the black-shale, lower member of the Bakken Formation of western North Dakota. The possibility exists that this member is as old as the *Palmatolepis perlobta postera* Biozone. The pelagic alga *Foerstia* occurs two metres above the base of the black shale in a position comparable to its occurrence in related black-shale units in the eastern United States.

A thin conchostracan bed at the top of the lower black shale, below the middle member of the Bakken, indicates continuation of anaerobic depositional conditions to the top of the black shale and strengthens the correlation of the Bakken with a dark shale-light siltstone-dark shale, Upper Devonian-Lower Mississippian, depositional complex widespread in the Western Interior.

Lower and upper units of the middle member imply deposition in oxygenated waters by bearing macrofossil assemblages precisely in the member of this sequence where conodonts are rare. A lower, bioturbated, massive, siltstone unit, unit 1, of the middle member carries a brachiopod and ichnofossil assemblage which allows correlation with the Late Devonian Louisiana Limestone of Missouri.

An overlying, cross-laminated, siltstone unit, unit 2, has "blade-like leaves" near its base as do basal beds in the area of the type Mississippian; this leads us to place the systemic boundary at the base of this unit in the deepest part of the Williston Basin.

An upper siltstone unit, unit 3, of the middle member resembles unit 1 of this member but bears a distinctly Mississippian brachiopod fauna, dominated by *Spirifer*, similar to that of the Early Mississippian McCraney Limestone of the Mississippian type area.

Black shale of the upper member of the Bakken signals a return to anoxic bottom conditions in the Basin; but it carries abundant conodonts of the Lower *Siphonodella crenulata* Biozone indicating an early, but not earliest, Mississippian age for this member.

Well-preserved conodonts (recovered by acidizing the Lodgepole Limestone) of the fauna of the Lower *Siphonodella crenulata* Biozone continue upward from the Bakken without

interruption across the sharp formational boundary into the basal Lodgepole but dwindle rapidly in numbers within 15 meters of the base of the Madison. The *Siphonodella isosticha* -Upper *Siphonodella crenulata* Biozone may be present within the Lower Lodgepole.

Although we have been able to document the biochronologic age of the Bakken Formation in North Dakota, much work remains to be done on this formation—so important in the geology of the Williston Basin.

ACKNOWLEDGEMENTS

Our program of studies grew out of a conversation, about the Bakken Formation, of the senior writer with Robert K. Aaker, then chief geologist of Conoco, Inc., and Sidney B. Anderson, North Dakota Geological Survey. It was given impetus by funds from Conoco provided to Rick L. Webster through the Department of Geology and the Engineering Experiment Station at UND. The residue from this grant has purchased our photographic equipment and aided in many other aspects of our study. We have benefited from the advice of Alan M. Cvancara and Richard D. LeFever; we have also been aided, throughout, by the cooperation of members of the North Dakota Geological Survey, encouraged by Lee C. Gerhard and Don L. Halvorson, former chairmen of the Department, assisted in photography by Robert J. Stevenson, Director of the NMAL for the MMRRI and the Department, and by H. Randall Haight of Biomedical Communications at the University, in drafting by Luke Savoy (North Dakota Geological Survey) and by Nancy Huber, and in conodont identification by Gilbert Klapper of the University of Iowa. Although much credit and our gratitude go to these people and organizations, any mistakes or misinterpretations are ours.

REFERENCES CITED

Achauer, C. W., 1959, Stratigraphy and microfossils of the Sappington Formation in southwestern Montana: Billings Geological Society, 10th Annual Field Conference, Guidebook, p.41-49.

Alexander, R. R., 1977, Growth, morphology and ecology of Paleozoic and opportunisitic brachiopods from Idaho-Utah: Journal of Paleontology, v. 51, no. 6, p. 1133-1149.

Brindle, J. E., 1960, Mississippian megafaunas in southern Saskatchewan: Saskatchewan Department of Mineral Resoures Report 45, 107 p., 29 pls.

Christopher, J. E., 1961, Transitional Devonian-Mississippian formations of southern Saskatchewan: Saskatchewan Department of Mineral Resources Report 66, 103 p.

Collinson, C. J., 1963, Collection and preparation of conodonts through mass production techniques: Illinois State Geological Survey Circular 343, 16 p.

Conkin, J. E. and Conkin, B. M., 1973, The paracontinuity and the determination of the Devonian-Mississippian boundary in the type Lower Mississippian area of North America: University of Louisville Studies in Paleontology and Stratigraphy No. 1, 34 p., 1 pl.

Cramer, D. D., 1986, Reservoir characteristics and stimulation techniques in the Bakken Formation and adjacent beds, Billings Nose area, Williston Basin: SPE 15166 Presented at the Rocky Mountain Regional Meeting of the Society of Petroleum Engineers, Billings, May 19-21, 1986, p. 331-338, 20 figs.

Dembicki, H., Jr., and Pirkle, F. L., 1985, Regional source rock mapping using a source potential rating index: American Association of Petroleum Geologists Bulletin, v. 69, no. 4, p. 567-581.

Dow, V. E., 1960, Magnetic separation of conodonts: Journal of Paleontology, v. 34, no. 4, p. 738-743.

Dow, W. G., 1974, Application of oil-correlation and source-rock data to exploration in Williston Basin: American Association of Petroleum Geologists Bulletin, v. 58, no. 7, p. 1253-1262.

Duffield, S. L., and Warshauer, S. M., 1979, Two-step process for extraction of microfossils from indurated organic shales: Journal of Paleontology, v. 53, no. 3, p. 747-748.

Gutschick, R. C., 1962, Arenaceous Foraminifera from oncolites in the Mississippian Sappington Formation of Montana: Journal of Paleontology, v. 36, no. 6, p. 1291-1304.

Gutschick, R. C., 1964 (1966), Transitional Devonian to Mississippian environmental changes in western Montana, In: Merriam, D. F. (ed.), Symposium on cyclic sedimentation: Kansas Geological Survey Bulletin 169, p. 171-181.

Gutschick, R. C., and Moreman, W. L., 1967, Devonian-Mississippian Boundary relationships along the cratonic margin of the United States, In: Owald, D. H. (ed.) International Symposium on the Devonian System, Calgary, Alberta: Alberta Society of Petroleum Geologists, v. 2, p. 1892-1899.

Gutschick, R. C., and Perry, T. G., 1959, Sappington (Kinderhookian) sponges and their environment: Journal of Paleontology, v. 33, no. 6, p. 977-985.

Gutschick, R. C., and Rodriguez, Joaquin, 1967, Brachiopod zonation and correlation of the Sappington Formation of western Montana: American Association of Petroleum Geologists Bulletin, v. 51, no. 4, p. 601-620.

Gutschick, R. C., and Rodriguez, Joaquin, 1977, Late Devonian-Early Mississippian trace fossils and environments along the Cordilleran miogeosyncline, western U.S., In: Crimes, T. P., and Harper, J. C. (eds.), Trace Fossils 2: Geological Journal Special Issue 9, Seel House Press, Liverpool, p. 195-208.

Gutschick, R. C., and Rodriquez, Joaquin, 1979, Biostratigraphy of the Pilot Shale (Devonian-Mississippian) and contemporaneous strata in Utah, Nevada, and Montana: Brigham Young University Geology Studies, v. 26, pt. 1, p. 37-63.

Gutschick, R. C., and Sandberg, C. A., 1970, Latest Devonian conchostracans along cordilleran miogeosyncline, Alberta, Montana, Utah, and Nevada (abs.): American Association of Petroleum Geologists Bulletin, v. 54, no. 5, p. 849-850.

Gutschick, R. C., and Sandberg, C. A., 1983, Mississippian continental margins of the conterminous United States, In: Stanley, D. J., and Moore, G. T. (eds.), The shelfbreak: critical interface on continental margins: Society of Economic Paleontologists and Min-

eralogists, Special Publication 33, p. 79-96.

Gutschick, R. C., McLane, Michael, and Rodriguez, Joaquin, 1976, Summary of Late Devonian-Early Mississippian biostratigraphic framework in western Montana, In: 1976 Field Conference Guidebook: Tobacco Root Geological Society, Montana Bureau of Mines and Geology Special Publication 73, p. 91-124.

Gutschick, R. C., Suttner, L. J., and Switek, M. J., 1962, Biostratigraphy of transitional Devonian-Mississippian Sappington Formation of southwest Montana, In: Symposium, The Devonian System of Montana and adjacent areas: Billings Geological Society, 13th Annual Field Conference, Guidebook, p. 78-89.

Hayes, M. D., 1984, Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota: Unpublished M.Sc. thesis, University of North Dakota, 178 p.

Hayes, M. D., 1985, Conodonts of the Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota: The Mountain Geologist, v. 22, no. 2, p. 64-77.

Hester, T. C., and Schmoker, J. W., 1983, Preliminary log-derived maps of the Bakken Formation, North Dakota and Montana portions of Williston Basin: U.S. Geological Survey Open-file Report 83-717, 125 p.

Huber, T. P., 1986, Conodont biostratigraphy of the Bakken and lower Lodgepole Formations (Devonian and Mississippian), Williston Basin, North Dakota: Unpublished M.Sc. thesis, University of North Dakota, 274 p.

Kingston, D. R., Dishroom, C. P., and Williams, P. A., 1983, Global basin classification system: American Association of Petroleum Geologists Bulletin, v. 67, no. 12, p. 2175-2193.

Klapper, Gilbert, 1966, Upper Devonian and Lower Mississippian conodont zones in Montana, Wyoming, and South Dakota: The University of Kansas Paleontological Contributions, Paper 3, 43 p., 6 pls.

Klapper, Gilbert, and Furnish, W. M., 1962, Devonian-Mississippian Englewood Formation in Black Hills, South Dakota: American Association of Petroleum Geologists Bulletin, v. 46, no. 11, p. 2071-2078.

Krystinik, K. B., and Charpentier, R. R., 1984, Developing an oil generation model for resource assessment of the Bakken Formation, U. S. portion of Williston Basin: U.S. Geological Survey Open-File Report 84-694, 23 p.

Kume, Jack, 1960, An investigation of the Bakken and Englewood Formations (Kinderhookian) of North Dakota and northwestern South Dakota: Unpublished M.Sc. thesis, University of North Dakota, 86 p., 3 pls.

Kume, Jack, 1963, The Bakken and Englewood Formations of North Dakota and northwestern South Dakota: North Dakota Geological Survey Bulletin 39, 87 p.

Lane, H. R., Sandberg, C. A., and Ziegler, Willi, 1980, Taxonomy and phylogeny of some Lower Carboniferous conodont and preliminary standard post-*Siphonodella* zonation: Geologica et Palaeontologica, v. 14, p. 117-164, 10 pls.

Lane, N. G., and Sevastopulo, G. D., 1986, Micromorph crinoid fauna of the McCraney Limestone (Mississippian, Kinderhookian) of western Illinois: Journal of Paleontology, v. 60, no. 3, p.736-743.

Leenheer, M. J., 1984, Mississippian Bakken and equivalent formations as source rocks in the western Canadian Basin: Organic Geochemistry, v. 6, p. 521-532.

Macqueen, R. W., and Sandberg, C. A., 1970, Stratigraphy, age, and interregional correlation of the Exshaw Formation, Alberta Rocky Mountains: Canadian Petroleum Geology Bulletin, V. 18, no.1, p. 32-66.

Matthews, R. D., 1983, *Foerstia* from the Antrim Shale (Devonian) of Michigan: Geology, v. 11, no. 6, p. 327-330.

Meissner, F. F., 1978, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana, In: The economic geology of the Williston Basin: Montana Geological Society, 24th Annual Conference, Williston Basin Symposium, p. 2027-227.

Merrill, G. K., 1984, Interfacial alternatives to the use of dangerous heavy liquids in micropaleontology: Journal of Paleontology, v. 59, no. 2, p. 479-481.

Murray, G. H., Jr., 1968, Quantitative fracture study—Sanish pool, McKenzie County, North Dakota: American Association of Petroleum Geologists Bulletin, v. 52, no. 1, p. 57-65.

Nordquist, J. E., 1953, Mississippian stratigraphy in northern Montana: Billings Geological Society, 4th Annual Field Conference, Guidebook, p. 68-82.

Price, L. C., Ging, T., Daws, E., Love, A., Pawlewicz, M., and Anders, D., 1984, Organic Metamorphism in the Mississippian-Devonian Bakken Shale, North Dakota portion of the Williston Basin, In: Woodward, J., Meissner, F. F., and Clayton, J. L. (eds.), Hydrocarbon source rocks of the greater Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 83-133.

Rodriguez, Joaquin, and Gutschick, R. C., 1967, Brachiopods from the Sappington (Devonian-Mississippian) Formation of western Montana: Journal of Paleontology v. 41, no. 2, p. 364-384., pls. 41-44.

Rodriguez, Joaquin, and Gutschick, R. C., 1970, Late Devonian-Early Mississippian ichnofossils from western Montana and northern Utah, In: Crimes, T. P., and Harper, J. C. (eds.), Trace fossils: Geological Journal, Special Issue 3, Seel House Press, Liverpool, p. 407-438, 10 pl.

Rodriguez, Joaquin, and Gutschick, R. C., 1975, Epibiontic relationships on a Late Devonian algal bank: Journal of Paleontology. v. 49, no. 6, p. 1112-1120, 5 text-figs.

Rodriquez, Joaquin,and Gutshick, R. C., 1978, A new shallow water *Schizophoria* from the Leatham Formation (Late Famennian), northeastern Utah: Journal of Paleontology, v. 52, no. 6, p. 1346-1355,1 pl.

Sandberg, C. A., 1965, Nomenclature and correlation of lithologic subdivisions of the Jefferson and Three Forks Formations of southern Montana and northern Wyoming: U.S. Geological Survey Bulletin, 1194-N, 18 p.

Sandberg, C. A., 1976, Conodont biofacies of Late Devonian *Polygnathus styriacus* Zone in western United States, In: Barnes, C. R. (ed.), Conodont paleoecology: Geological Association of Canada Special Paper 15, p. 171-186.

Sandberg, C. A., 1979, Devonian and Lower Mississippian conodont zonation of the Great Basin and Rock Mountains, In: Sandberg, C. A., and Clark, D. L. (eds.), Conodont biostratigraphy of the Great Basin and Rocky Mountains: Brigham Young University Geology Studies, v. 26, pt. 3, p. 87-105.

Sandberg, C. A., and Gutschick, R. C., 1969, Stratigraphy and conodont zonation of type Leatham Formation (Devonian and Mississippian) Bear River Range, Utah (abs.): Geological Society of America Abstracts with Programs 1969, pt. 5, p. 70-71.

Sandberg, C. A., and Gutschick, R. C., 1979, Guide to conodont biostratigraphy of Upper Devonian and Mississippian rocks along the Wasatch Front and Cordilleran Hingeline, Utah, In: Sandberg, C. A., and Clark, D. L. (eds.), Conodont biostratigraphy of the Great Basin and Rocky Mountains: Brigham Young University Geology Studies, v. 26, pt. 3, p. 107-134.

Sandberg, C. A., and Hammond, C. R., 1958, Devonian System in Williston Basin and central Montana: American Association of Petroleum Geologists Bulletin, v. 42, no. 10, p. 2293-2334.

Sandberg, C. A., and Klapper, Gilbert, 1967, Stratigraphy, age, and paleotectonic significance of the Cottonwood Canyon Member of the Madison Limestone in Wyoming and Montana: U.S. Geological Survey Bulletin 1251-B, 70 p.

Sandberg, C. A., and Mapel, W. J., 1967, Devonian of the Northern Rocky Mountains and Plains, In: Oswald, D.H. (ed.), International Symposium on the Devonian System, Calgary, Alberta: Alberta Society of Petroleum Geologists, v. 1, p. 843-877.

Sandberg, C. A., and Pole, F. G., 1977, Conodont biostratigraphy and depositional complexes of Upper Devonian cratonic-platform and continental-shelf rocks in western United States, In: Murphy, M. A., Berry, W. B. N., and Sandberg, C. A., (eds.), Western North American, Devonian: California University, Riverside, Campus, Museum Contributions 4, p. 144-182.

Sandberg, C. A., Poole, F. G., and Gutschick, R. C., 1980, Devonian and Mississippian stratigraphy and conodont zonation of Pilot and Chainman Shales, Confusion Range, Utah, In: Fouch, T. D., and Magathan, E. R. (eds.), Paleozoic paleogeography of the west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 1, p. 71-79.

Sando, W.J., 1967, Mississippian depositional provinces in the northern Cordilleran Region: U.S. Geological Survey Professional Paper 575-D, p. D29-D38.

Schmoker, J. W., and Hester, T. C., 1983, Organic carbon in the Bakken Formation, U.S. portion of the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 67, no. 12, p. 2165-2174.

Scott, A. J., and Collinson, C. W., 1961, Conodont faunas from the Louisiana and McCraney Formations of Illinois, Iowa, and Missouri, In: Malone, D. J. (ed.), Guidebook twenty-sixth annual field conference, northeastern Missouri and west central Illinois: Kansas Geological Society, p.110-141.

Spencer, C. W., 1987, Hydrocarbon generation as a mechanism for overpressuring in Rocky Mountain region: American Association of Petroleum Geologists Bulletin, v. 71, no. 4, p. 368-388.

Sprinkle, James, and Gutschick, R. C., 1967 *Costatoblatus* a channel fill blastoid from the Sappington Formation of Montana: Journal of Paleontology, v. 4, no. 2, p. 385-402, pl. 45.

Thode, H. G., 1981, Sulfur isotope ratios in petroleum research and exploration—Williston Basin: American Association of Petroleum Geologists Bulletin, v. 65, no. 9, p. 1527-1535.

Thrasher, L. C., 1985, Macrofossils and biostratigraphy of the Bakken Formation (Devonian and Mississippian) in western North Dakota: Unpublished M.Sc. thesis, University of North Dakota, 292 p.

Webster, R. L., 1982, Analysis of petroleum source rocks of the Bakken Formation (Devonian and Mississippian) in North Dakota: Unpublished M.Sc. thesis, University of North Dakota, 150 p.

Williams, J. A., 1974, Characterization of oil types in the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 58, no. 7, p. 1242-1252.

Wilson, B. J., 1983, Petroleum production and petroleum geology of the Bakken Formation, Williston Basin, North Dakota: The Compass of Signa Gamma Epsilon, v. 60, no. 4, p.99-110.

Ziegler, Willi, 1962, Taxionomie und Phylogenie Oberdevonischer Conodonten and ihre stratigraphische Bedeutung: Weisbaden Hessisches Landesamt Bodenforschung, heft 38, 166 p., 14 pls.

Ziegler, Willi, 1970 (1971), Conodont stratigraphy of the European Devonian, In: Sweet, W. C., and Bergstrom, S. M. (eds.), Symposium on conodont biostratigraphy: Geological Society of America, Memoir 127, p. 227-284.

Ziegler, Willi, and Sandberg, C. A., 1984, *Palmatolepis* - based revision of upper part of standard Late Devonian conodont zonation, In: Clark, D. L. (ed.), Conodont biofacies and provincialism: Geological Society of America Special Paper 196, p.179-194.

THE MADISON, A NOMENCLATURAL REVIEW WITH A LOOK TO THE FUTURE

CLARENCE G. CARLSON[1] AND JULIE A. LEFEVER[2]

[1]North Dakota Industrial Commission
Oil and Gas Division
900 East Boulevard
Bismarck, North Dakota 58505

[2]North Dakota Geological Survey
University Station
Grand Forks, North Dakota 58202

ABSTRACT

The difficulty of extending nomenclature applied to Madison strata of the outcrops in Montana into the subsurface in the Williston Basin was recognized early and led to the addition of the Charles Formation to the Madison Group in the subsurface of eastern Montana. Recognition of facies changes across the Basin led to the use of marker horizons to delineate marker-defined units within Madison strata on the east flank of the Basin. Numerous terms were introduced for marker-defined units and different horizons were used in different areas for similar terms. Exploration has now provided a means for establishing the stratigraphic relationships of the marker-defined units, and a review of the stratigraphic code provides a basis for clarifying nomenclature.

It is herein proposed that the lithostratigraphic terms Madison Group, Charles, Mission Canyon, and Lodgepole Formations be retained as formal stratigraphic units. The facies relationships of the evaporites and carbonates are recognized by placing the Charles-Mission Canyon contact at progressively lower stratigraphic horizons towards the east flank of the Basin, so that the lowest evaporites are in the Charles Formation. The marker-defined units or marker horizons are considered informal units and may be referred to as intervals, subintervals, cycles, formats, marker horizons, or facies.

NOMENCLATURAL REVIEW OF THE MADISON

Nomenclature applied to strata of the Madison Group in the Williston Basin has evolved from attempts to extend surface terminology into the subsurface. It was recognized quite early that there were problems in extending these terms from the surface into the subsurface if one were to follow the code of stratigraphic nomenclature, because of facies changes across the region. This has led to a variety of solutions with the introduction of numerous informal names for units or for marker horizons within the Madison. It is the purpose of this paper to review past practice and present some alternatives which might lead to a more uniform usage.

The term Madison Limestone was introduced by Peale (1893) for carbonates that he described as 575 feet of massive "jaspery" limestone, 350 feet of light bluish gray, massive limestone and 325 feet of dark colored, compact, laminated limestone that is well exposed in the Madison Range of Montana (Fig. 1). Collier and Cathcart (1992) recognized that the Madison Limestone was divisible into two distinct formations in the Little Rocky Mountains (Fig. 1). They introduced the terms Mission Canyon for massive white limestone and the term Lodgepole for 800 feet of thin-bedded limestone and shale, below. Seager (1942) used the term Charles, derived

Fig. 1 - Location map showing the outline of the Williston Basin, the location of the Madison Range and the Little Rocky Mountains.

from the Arro, California Company-Charles No. 4 well (SE/4 NW/4 Sec. 21, T.15N., R.30E.), to describe a series of interbedded limestone, dolomite, anhydrite, and shale beds overlying the Mission Canyon limestone in the Carter Oil - N.P. No. 1 well (SW/4 SE/4 Sec. 19, T.4N., R.62E.) in Montana (Fig. 1).

He placed the Charles strata in the Big Snowy Group while noting that they might belong in the Madison Group. Perry and Sloss (1943) included the interval from 3,050 to 3,810 feet in the Charles No. 4 well in the Charles Formation. Nordquist (1953) noted that this interval included what was then recognized as limestone and fine-grained clastics of the Kibbey Formation. Therefore, he redefined the Charles Formation by placing the top at the top of a massive salt which is present over extensive areas of the Basin and is found at a depth of 3,195 feet in the Charles No. 4 well.

Harrison and Flood (1956, p. 37) used the terms Lodgepole, Mission Canyon, and Charles Formations to continue then current usage in the North Dakota portions of the Basin while recognizing "that in a true lithologic sense these rock units may not be exact equivalents of the type sections." They recognized a series of cyclical carbonates and evaporites on the Basin flank that they designated as equivalent to the Charles Formation. They used the informal units C-1 through C-8 to represent 8 cycles (1956, p. 38) with the base of the C-1 cycle as the top of the Mission Canyon Formation in all areas (Fig 2*).

In Saskatchewan, the cyclical succession was also recognized; however, it was also recognized that the evaporite facies existed at progressively lower stratigraphic positions towards the Basin margin (Thomas, 1954; Porter, 1955; Fuller, 1956). These authors suggested that marker beds within Madison strata are nearly time-parallel and are useful for dividing these strata into paratime rock units which they termed "beds". Thomas (1954) retained the use of Lodgepole, Mission Canyon, and Charles Formations, while Porter used these terms as facies while using marker-defined beds (Fig. 2). Fuller (1956), p. 30) used Charles evaporite and Madison limestone, which he divided into lower and upper units. The upper Madison was divided into marker-defined units. In regard to the Charles he stated (p. 32), "On lithological grounds all the evaporitic beds intertonguing with Madison limestone on the Basin flank, . . . could be included in the Charles Formation, but the result would lack utility . . . at the present the top of the Ratcliffe may be a more useful approximation" for the base of the Charles.

The Mississippian Names and Correlations Committee of the Saskatchewan Geological Society (1956) introduced the terms Poplar, Ratcliffe, Midale, Frobisher-Alida, Tilston, and Souris Valley "beds" for marker-defined units within the Madison. While some of these names are the same as those of Fuller (1956), different marker horizons were used for the contacts of these "beds" (Fig. 2).

Edie (1958, Fig. 3) used a combination of the facies and marker-defined units with his contacts of the Lodgepole, Mission Canyon, and Charles Formations at progressively lower stratigraphic horizons towards the eastern margin of the Basin. He noted that (p. 96) if the marker-defined terminology were to gain acceptance, "The terms Charles and Mission Canyon which refer essentially to rock stratigraphic units would gradually come into disuse."

The Mississippian Committee of the North Dakota Geological Society (1959) published an interim report in which they reclassified the Madison Group into the Lodgepole, Mission Canyon, and Charles facies. Then they used marker horizons to divide the Madison into Poplar, Ratcliffe, Frobisher-Alida, Tilston, and an unnamed "member" with the "members" crossing the facies boundaries. They retained Canadian terms because of their priority, although they used what they considered to be more persistent marker horizons for defining these units. A final report was never published, but Smith (1960, p. 959) referred to these marker-defined units as "intervals" and "subintervals" (Fig. 2).

The North Dakota Geological Survey accepted the conclusions of the Mississippian Committee in regard to defining the marker horizons and added the term Bottineau interval as the lowest unit. The upper intervals and subintervals were defined by Anderson and others (1960, Fig. 3) and terminology for the complete Madison section was given by Ballard (1963, Figs. 4, 5, 6).

The Special Studies Committee of the Billings Geological Society (1964) correlated formation boundaries for the Lodgepole, Mission Canyon, and Charles Formations by means of radioactivity characteristics. They said (p. 105), "Grossly, each formation has dominant lithologic characteristics, but the lithology of one may transcend across the boundary into another formation or there may be a diverse lithology within a formation".

In Manitoba, McCabe (1959) recognized the general utility of the Lodgepole, Mission Canyon, and Charles while also recognizing the marker-defined units (Fig. 2). He placed the Charles-Mission Canyon contact at progressively lower horizons towards the Basin margin while referring to marker-defined units within these strata as formats (Forgotson, 1957). He referred to subdivisions of the Lodgepole Formation as members.

Harris and others (1966) used the terms Lodgepole, Mission Canyon, and Charles Formations for Madison strata in north-central North Dakota. They placed the base of the Charles Formation at a marker horizons called the "State A marker." They considered their upper Mission Canyon to be equivalent to the Frobisher-Alida "beds" of Saskatchewan. They recognized and named six cyclic, marker-defined units in the Upper Mission Canyon which they referred to as beds (Fig. 2). As the marker horizons became indistinct southwestward into the Basin they used an undifferentiated upper Mission Canyon in that area.

REVIEW OF THE CODE

The last 20 years have seen a general acceptance of the marker-defined units for Madison strata in the Williston Basin, but, contrary to Edie's expectations, at least in the United States portion of the Basin, the terms Charles and Mission Canyon have not gone into disuse. Perhaps a brief review of pertinent aspects of the North American Stratigraphic Code may be useful as we assess the desirability of using Madison terminology in conformity with the Code in the Williston Basin.

The North American Commission on Stratigraphic Nomenclature (1983) wrote in the preamble to the Code that a lithostratigraphic unit (p. 848) is a "stratum or body of strata, generally but not invariably layered, generally but not invariably tabular, which conforms to the law of superposition and is distinguished and delineated on the basis of lithic characteristics and stratigraphic position." The formation is the fundamental unit in lithostratigraphic classification (Art. 24). Where formal recognition of smaller units serve a useful purpose they may be established as members and beds (Art. 24, d). A geographically restricted member may be called a lens or tongue (Art. 25, b). Although members normally are in vertical sequence, laterally equivalent parts of a formation that differ recognizably may also be considered members (Art. 25, e). A bed, or beds, is the smallest formal lithostratigraphic unit (Art. 26). Group is the unit of next higher rank than formation (Art. 28).

Units defined exclusively on the basis of remotely sensed physical properties (e.g., borehole logs), although commonly useful in stratigraphic analysis, stand completely apart from the hierarchy of formal lithostratigraphic units and are considered informal (Art. 22, h). As applied to the designation of lithostratigraphic units, the term "zone" is informal (Art. 22, c). Cyclic or rhythmic sequences have been named

* *Figure 2, a correlation chart, is provided as a separate sheet.*

cyclothems (cycles); where they have been identified by geographic names, such names are considered informal (Art. 22, j). Depositional facies are informal units (Art. 22, i).

The preamble to the Code said (p. 847), "a stratigraphic code or guide is a formulation of current views on stratigraphic principles and procedures designed to promote standardized classification and formal nomenclature of rock materials . . . . Because any code embodies only current concepts and principles, it should have the flexibility to provide for both changes and additions to improve its relevance to new scientific problems."

Forgotson (1957, p. 2105) proposed that, "Marker-defined units should be formally defined and named because in subsurface correlations and mapping they are one of the most widely used classes of rock units." He then proposed (p. 2110), that, "The term format would apply to marker-defined operational units that are segregations of strata sandwiched between markers which can be traced through facies changes." Such a definition quite precisely describes the units within the Madison strata which have been referred to as "beds" or "intervals" in the Williston Basin although in the Basin, Forgotson's term has only been used in Manitoba (McCabe, 1959, 1963).

The Commission specifically rejected Forgotson's proposal (p. 851) while recognizing a need for informal units: "Informal terms are devised for both economic and scientific reasons. Formalization is appropriate for those units requiring stability of nomenclature, particularly those likely to be extended far beyond the locality in which they were first recognized. Informal terms are appropriate for . . . those defined by unconventional criteria."

Clearly it has been recognized for more than 30 years that marker-defined units are of utility in discussion of stratigraphy of Madison strata in the Williston Basin. It is also clear that the Code considers these to be informal units. The question then becomes: Is it desirable to follow the Code for these strata? If so, what are the appropriate terms?

The term "Beds" was introduced for the marker-defined units in Saskatchewan to differentiate these para-time rock units from the lithostratigraphic term beds at a time when formal lithostratigraphic terms were not capitalized. Subsequent usage has not always so clearly enunciated this distinction, but clearly marker-defined units are classified as informal units. A complication which has plagued clarity has been the practice of retention of names for marker-defined units and revision of boundaries. The Code says (Art. 19a, p. 855) "Revision is justifiable if a minor change in boundary or content will make a unit more natural and useful." In the United States it was felt that it would be "more natural and useful" to use the most extensive marker horizons for definition of units.

A LOOK TO THE FUTURE

The prominent gamma-ray marker referred to as the "first Madison marker" (North Dakota Geological Society, 1959) and commonly referred to as the "green point" or "Ratcliffe" was been used to define the base of the Poplar interval (Anderson and others, 1960; Bluemle and others, 1980). The "second Madison marker" (North Dakota Geological Society, 1959) referred to as "Top of main pay" or "Nesson main pay" by industry was used to define the top of the Frobisher-Alida interval and Rival subinterval in Burke County (Anderson and others, 1960). The MC-2 marker (Thomas, 1954) was used to define the top of the Tilston interval on the northeast flank of the Basin. The Bottineau interval is recognized by the change in log characteristics from the clean carbonates of the Tilston interval to argillaceous and siliceous carbonates.

The Billings Geological Society (1964) used the same gamma-ray markers for correlation in the Madison of Montana. They used the "first Madison marker" as the base of their "Poplar Beds" in the Charles Formation. They used the "second Madison marker" as the top of the Mission Canyon Formation. They placed the contact between the Mission Canyon and Lodgepole Formations at the base of "clean carbonate" gamma-ray characteristics.

Terminology applied to the marker-defined units has commonly used "beds" with an implied para-time rock connotation. Since beds may be recognized as a formal rank of lithostratigraphic units in the Code, we suggest that the marker-defined units should more clearly be identified as informal units by use of such terms as intervals, subintervals, markers, formats, cycles, or facies. In the Canadian portion of the Basin, where similar names have been used for different units, confusion might be avoided if workers continue to use "Beds" for Canadian units. Thus Ratcliffe Beds would imply the Canadian definition and Ratcliffe interval would imply the North Dakota definition. In the alternative, if they felt that "Beds" might be confusing between informal and formal units, use of cycle or format, such as has been done in Manitoba, would serve the same purpose.

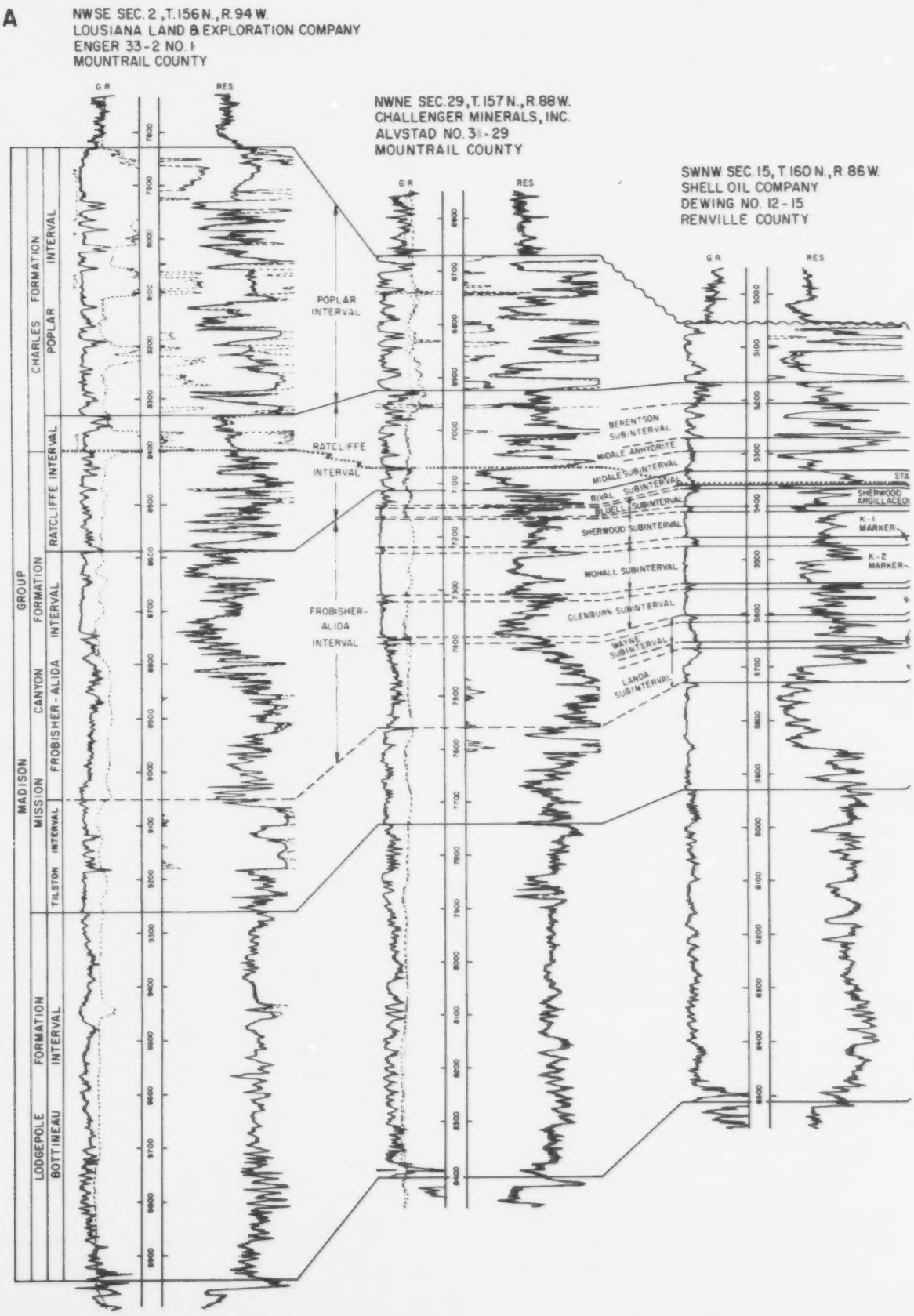
One alternative is to disregard the Code and use the lithostratigraphic terms formation, member, and bed in a utilitarian sense. The base of the Charles Formation is then placed at a convenient marker horizon. This has commonly been done with use of the "second Madison marker" (Billings Geological Society, 1964), base of "State A marker" (Harris and others, 1966), or base of C-1 cycle (Harrison and Flood, 1956). Marker-defined units or beds, thus, are then confined to the same formation.

If we are to conform to the Code, the terms Madison Group and Lodgepole, Mission Canyon, and Charles Formations should be used in combination with informal units (Fig. 3). The Charles, as orginally defined, refers to interbedded carbonates and evaporites. Using that definition,the contact between the Charles and Mission Canyon Formations should be placed at progressively lower stratigraphic positions toward the Basin margin, as has commonly been done (Porter, 1955; Fuller, 1956; Ballard, 1963; McCabe, 1963). The marker-defined units should then be used as informal units that may be present in both formations.

Detailed studies on the east flank of the Basin have led to recognition of numerous marker-defined units within the intervals. A combination of subintervals, markers, or facies (anhydrites) may be used to adequately define these smaller, informal units (Fig. 3). This practice should provide adequate flexibility, lead to clarity, and hopefully lend stability to the nomenclature.

ACKNOWLEDGEMENTS

We wish to thank Dr. F. D. Holland, Jr. and Dr. Richard D. LeFever for critical review of the manuscript. We should also like to thank Sidney B. Anderson, Acting State Geologist for review of Figures 2 and 3.


A
NWSE SEC. 2, T. 156 N., R. 94 W.
LOUSIANA LAND & EXPLORATION COMPANY
ENGER 33-2 NO. 1
MOUNTRAIL COUNTY
NWNE SEC. 29, T. 157 N., R. 88 W.
CHALLENGER MINERALS, INC.
ALVSTAD NO. 31-29
MOUNTRAIL COUNTY
SWNW SEC. 15, T. 160 N., R. 86 W.
SHELL OIL COMPANY
DEWING NO. 12-15
RENVILLE COUNTY
GR
RES
MADISON GROUP
LODGEPOLE FORMATION
BOTTINEAU INTERVAL
MISSION CANYON FORMATION
TILSTON INTERVAL
FROBISHER-ALIDA INTERVAL
CHARLES FORMATION
RATCLIFFE INTERVAL
POPLAR INTERVAL
POPLAR INTERVAL
RATCLIFFE INTERVAL
FROBISHER-ALIDA INTERVAL
BERENTSON SUBINTERVAL
MIDALE ANHYDRITE
MIDALE SUBINTERVAL
RIVAL SUBINTERVAL
BLUELL SUBINTERVAL
SHERWOOD SUBINTERVAL
MOHALL SUBINTERVAL
GLENBURN SUBINTERVAL
WAYNE SUBINTERVAL
LANDA SUBINTERVAL
STA
SHERWOOD ARGILLACEO
K-1 MARKER
K-2 MARKER

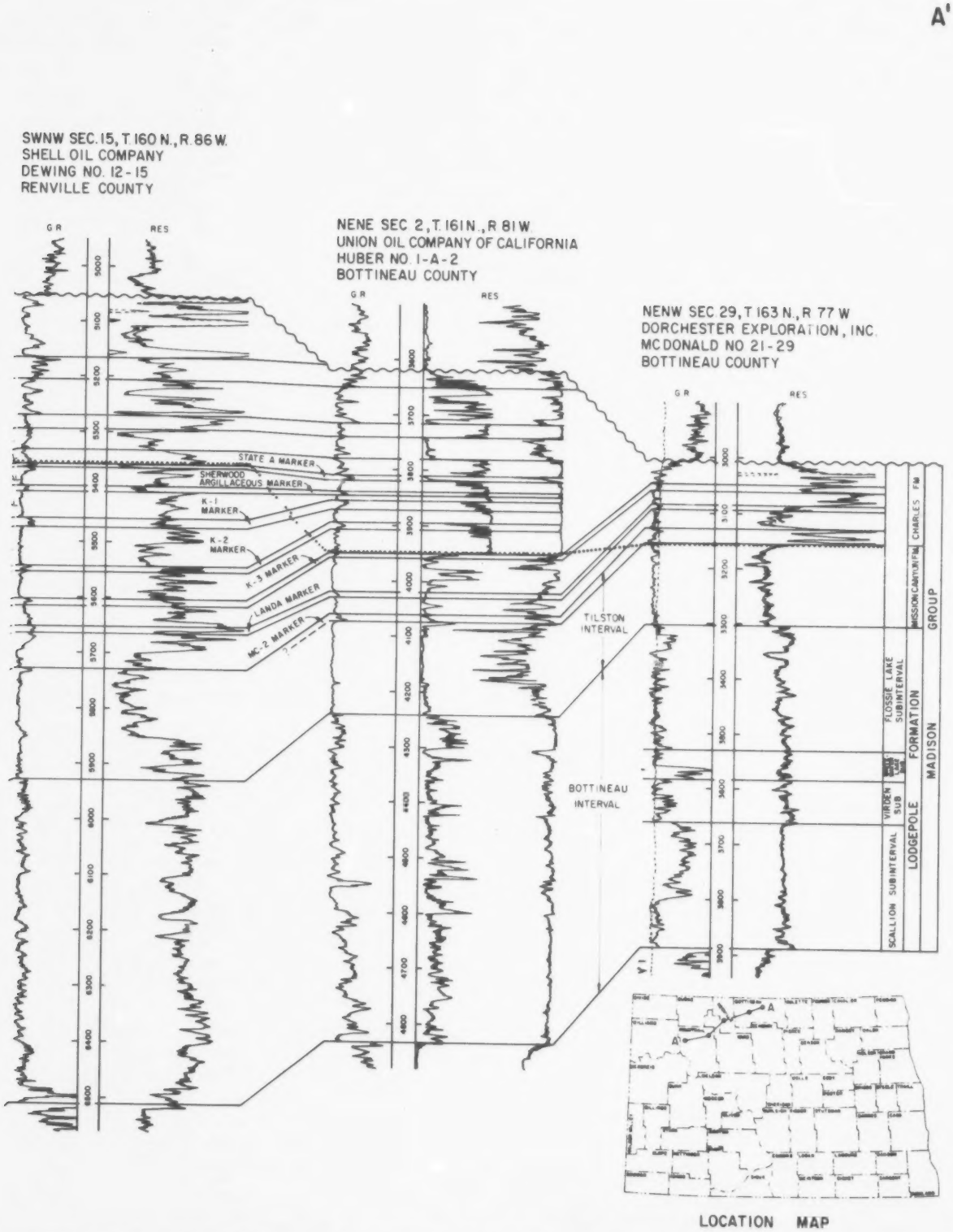


Fig. 3 - Cross-section of Madison rocks from Bottineau County to the center of the Williston Basin, North Dakota. The reader is referrd to LeFever and Anderson (1986) for a more detailed study of the proposed subintervals and marker beds for north-central North Dakota.

REFERENCES CITED

Anderson, S. B., 1958, Mississippian possibilities: World Oil, v. 147, no. 7, p. 136-144.

Anderson, S. B., Hansen, D. E., and Eastwood, W. P., 1960, Oil fields in the Burke County area, North Dakota - geological, magnetic, and engineering studies: North Dakota Geological Survey Report of Investigation No. 36, 71 p.

Anderson, S. B., Nelson, L. B., 1956, Mississippian stratigraphic studies: North Dakota Geological Survey Report of Investigation No. 24.

Ballard, F. V., 1963, Structural and stratigraphic relationships in the Paleozoic rocks of eastern North Dakota: North Dakota Geological Survey Bulletin No. 40, 38 p.

Billings Geological Society Special Studies Committee, 1964, Lower Mississippian correlations of eastern Montana: Third International Williston Basin Symposium, p. 105-108.

Bluemle, J. P., Anderson, S. B., and Carlson, C. G., 1980, North Dakota stratigraphic column.

Collier, A. J., and Cathcart, S. H., 1922, Possibility of finding oil in Laccolithic domes south of the Little Rocky Mountains: U.S. Geological Survey Bulletin 736F, pt. 2, p. 171-178.

Edie, R. W., 1958, Mississippian sedimentation and oil fields of southeastern Saskatchewan: American Association of Petroleum Geologists Bulletin, v. 42, p. 94-126.

Forgotson, J. M., Jr., 1957, Nature and usage and definition of marker-defined vertically segregated rock units: American Association of Petroleum Geologists Bulletin, v. 41, p. 2108-2112.

Fuller, J. G. C. M., 1956, Mississippian rocks and oil fields in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 19, 72 p.

Fuzesy, L. M., 1960, Correlation and subcrops of the Mississippian strata in southeastern and south-central Saskatchewan: Saskatchewan Department of Mineral Resources Report 51, 63 p.

Gries, J. P., and Mickelson, J.C., 1964, Mississippian carbonate rocks of western South Dakota and adjoining areas: Third International Williston Basin Symposium, p. 105-108.

Harris, S. H., Land, C.B., Jr., and McKeever, J. H., 1966, Relation of Mission Canyon stratigraphy to oil production in north-central North Dakota: American Association of Petroleum Geologists Bulletin, v. 50, p. 2269-2276.

Harrison, R. L., and Flood, A. L., 1956, Mississippian correlations in the international boundary area: First International Williston Basin Symposium, p. 36-51.

LeFever, J. A., and Anderson, S. B., 1986, Structure and stratigraphy of the Frobisher-Alida and Ratcliffe intervals, Mississippian Madison Group, north-central North Dakota: North Dakota Survey Report of Investigation No. 84, 17 p.

McCabe, H. R., 1959, Mississippian stratigraphy of Manitoba: Manitoba Mines Branch Publications 58-1, 99 p.

McCabe, H. R., 1963, Mississippian oilfields of southwestern Manitoba: Department of Mines and Natural Resources Publication 60-5, 50 p.

Nordquist, J.W., 1953, Mississippian strata of northern Manitoba: Billings Geological Society 4th Annual Field Conference, p. 68-82.

North American Commission on Stratigraphic Nomenclature, 1983, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841-875.

North Dakota Geological Society, 1959, Mississippian Committee interim report: Bismarck, North Dakota Geological Society Geologram, v. 2, p. 1-3.

Organ, D. W., and Russin, G. M., 1956, Mississippian stratigraphy of the Daly Oil Field: Canadian Institute of Mining and Metallurgy, v. 49, p. 193-198.

Peale, T. A. C., 1893, The Paleozoic section in the vicinity of Three Forks, Montana: U.S. Geological Survey Bulletin 110.

Perry, S. S., and Sloss, L. L., 1943, Big Snowy Group: Lithology and correlation in the northern Great Plains: American Association of Petroleum Geologists Bulletin, v. 27, p. 1299-1301.

Peterson, J.A., 1984, Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273-A, 34 p.

Porter, J. W., 1955, Madison complex of southeastern Saskatchewan and southwestern Manitoba: Journal of the Alberta Society of Petroleum Geologists, v. 3, p. 126-130.

Saskatchewan Geological Society, 1953, Report of the committee on Mississippian nomenclature: Saskatchewan Geological Society, Regina, Saskatchewan.

Saskatchewan Geological Society, 1956, Report of the Mississippian names and correlation committee: Saskatchewan Geological Society, Regina, Saskatchewan.

Seager, D. A., 1942, Test on the Cedar Creek anticline, southeastern Montana: American Association of Petroleum Geologists Bulletin, v. 26, p. 861-864.

Smith, M. H., 1960, Revised nomenclature for Williston Basin: American Association of Petroleum Geologists Bulletin, v. 44, p. 959-960.

Stanton, M. H., 1955, Stratigraphy of the Lodgepole Formation, Virden-Whitewater area, Manitoba: Journal of the Alberta Society of Petroleum Geologists, v. 4, p. 164-167.

Thomas, G.E., 1954, The Mississippian of the northern Williston Basin: Canadian Institute of Mining and Metallurgy Transactions, v. 57, p. 68-74.

CORALS FROM THE MADISON GROUP, WILLISTON BASIN, NORTH DAKOTA

DOUGLAS L. WATERS[1] AND WILLIAM J. SANDO[2]

[1]*ARCO Alaska Inc.*
Anchorage, AK 99510-0360

[2]*U.S. Geological Survey, U.S. National Museum of Natural History*
Washington, D.C.

ABSTRACT

Study of cores from the Madison Group (Mississippian) in 29 wells in the Williston Basin of North Dakota revealed a coral fauna represented by eleven species and four morphogroups belonging to the genera *Amplexocarinia, Amplexizaphrentis, Cyathoxonia, Lophophyllum, Michelinia, Siphonodendron, Stelechophyllum, Synchoelasma, Syringopora*, and *Vesiculophyllum*. Four zonules based on corals are useful for correlation of Mississippian rocks within the area studied. *Stelechophyllum micrum* and *S. banffense* are recorded in the conterminous United States for the first time.

INTRODUCTION

Corals are among the few fossils that have proved useful for dating and correlating Mississippian rocks in the Williston Basin (Brindle, 1960; Sando, 1960, 1978). Study of cores from the Madison Group in 29 wells in the Williston Basin of North Dakota revealed a coral fauna of relatively low diversity and abundance. Despite obvious inluences of inhospitable environments on the distribution of these corals, a sequence of zonules useful for correlation within the area studied was determined (Waters and Sando, 1987). The purpose of this paper is to describe and illustrate the corals used in this study.

PALEOGEOGRAPHY AND STRATIGRAPHY

The area studied was part of a broad shelf characterized mostly by shallow-water carbonate environments during Mississippian time (Figure 1). Biogeographically, the area was in the Western Interior Province of Sando and others (1975, 1977).

This study uses the informal subsurface Madison terminology of the North Dakota Geological Survey (Smith, 1960; Anderson and others, 1960; Eastwood, 1961; Ballard, 1963; Carlson and Anderson, 1966) superimposed on formal Madison lithostratigraphic units (Figure 2). The coral fauna contains repesentatives of Coral Zones 1 through IIIA of Sando and Bamber (1979, 1985) (Figure 2).

A sequence of local zonules useful for correlation and dating in western North Dakota (Figure 2) is fully described in Waters and Sando (1987). Composite stratigraphic ranges of all taxa in the area studied are shown on Figure 3. The distribution of taxa in lithic facies and inferred depositional environments is described in Waters and Sando (this volume).

SYSTEMATIC PALEONTOLOGY

Morphologic terminology and biologic classification follow Hill (1981). All specimens are deposited in the paleontological collections of the University of North Dakota (UND). Detailed occurrence data are given in Waters and Sando (1987 and this volume). Positions of collections in the core are given in feet below the kelly bushing (KB), which is a level slightly above the derrick floor.

Phylum Coelenterata Fry and Leukart, 1847

Subphylum Cnidaria Hatschek, 1888

Class Anthozoa Ehrenberg, 1834

Subclass Rugosa Milne-Edwards and Haime, 1850

Order Staurida Verrill, 1865

Suborder Metriophyllina Spasskiy, 1965

Family Cyathaxoniidae Milne-Edwards and Haime, 1850

Genus *Cyathoxonia* Michelin, 1847

Cyathocarinia Soshkina, 1928, p. 376.

Type species. - *Cyathoxonia cornu* Milne-Edwards and Haime, 1850.

Diagnosis. - Small, ceratoid to cylindrical rugose corals. Cylindrical columella developed independently of major septa but in contact with them. Minor septa long, contratingent, inserted between major septa. Tabulae declined abaxially. No dissepiments. Septa may be tuberculated. (From Sando and Bamber, 1985; and Hill, 1981, p. 186.)

Discussion. - Sando (1977) emended the genus to include tuberculated forms referred to *Cyathocarinia* Soshkina, 1928. Sando (1960, p. 168; 1978, Plate 1) reported only a small number of specimens of *Cyathaxonia* from the Madison, and these were mostly from the Lodgepole Limestone. In the present study, *Cyathaxonia* was found to be a major constituent of the coral fauna.

Cyathaxonia sp.
Figure 4.1 - 4

Although the Williston Basin specimens seem to compare favourably in size and number of septa with *Cyathaxonia tantilla* (Miller) described by Sando (1977, p. 55), tuberculated septa were not always observed. Without an ontogenetic study of these specimens, we hesitate to assign them to *C. tantilla*.

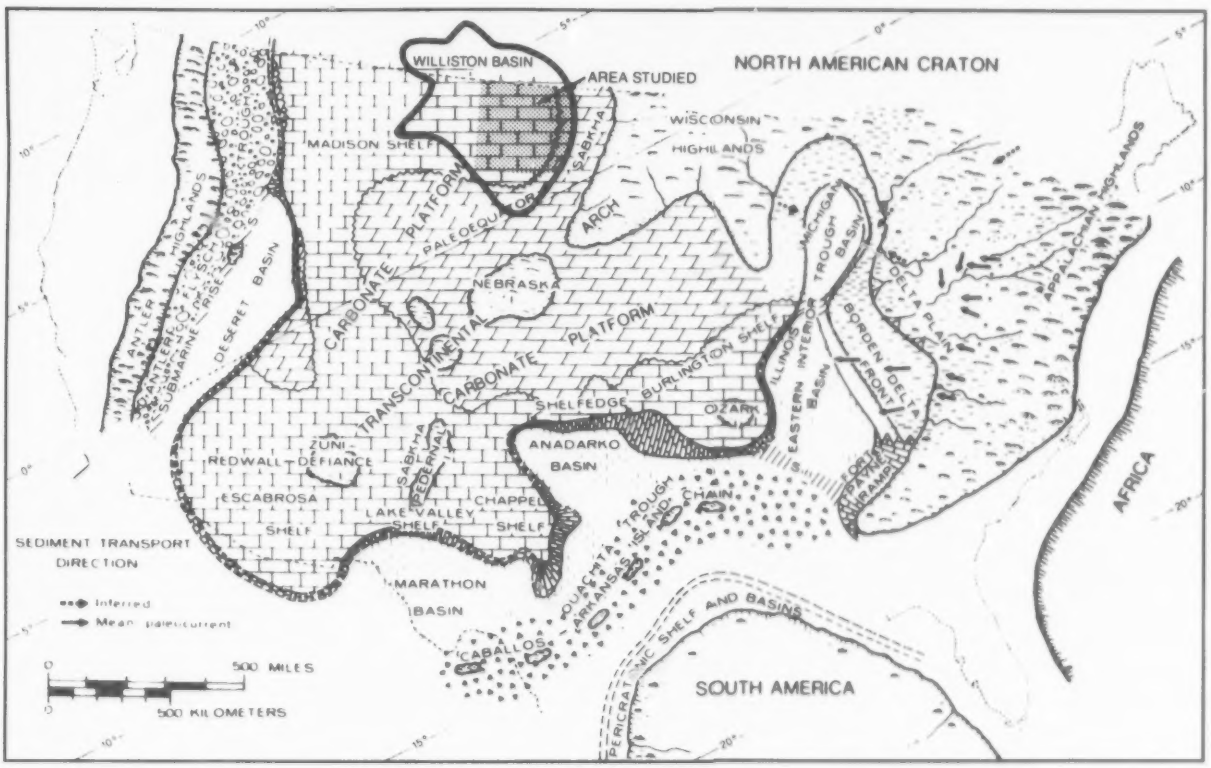


Fig. 1 Paleogeographic and lithofacies map of the conterminous United States during middle Mississippian time (from Gutschick and Sandberg, 1983, p. 84), showing location of area studied.

Specimens of *Cyathaxonia* in the Williston Basin of North Dakota are 3 to 4.5 mm in diameter. A longitudinal section of one ceratoid specimen measured 10 mm in length. Specimens with a diameter between 3.5 and 4.5 mm have 35 to 36 ordinarily tuberculated septa. Major septa are in contact with columella.

Occurrence. - Only a few specimens of *Cyathaxonia* sp. were observed in the Bottineau interval in NDGS Well No. 607, at 10,495 to 10,503 feet below KB, and NDGS Well No. 2171, at 10,125 feet below KB.

Cyathaxonia sp. is abundant in the lower Mission Canyon (Tilston and lower Frobisher-Alida intervals). At least 12 per cent of the coral specimens from North Dakota belong to this genus.

Family Laccophyllidae Grabau, 1928

Subfamily Amplexocariniinae Soshkina, 1928

Genus *Amplexocarinia* Soshkina, 1928

Amplexicarinia Lang, Smith and Thomas, 1940, p. 16.

Type species. - *Amplexocarinia muralis* Soshkina, 1928.

Diagnosis. - Small, ceratoid to cylindrical rugose corals having wide aulos formed by downturned edges of axial tabulae. Major septa short, touching aulos. Minor septa absent or poorly developed. Within aulos, tabulae horizontal; outside aulos, tabulae sloping downward to periphery. Dissepiments usually absent but present in some species. (From Sando and Bamber, 1985.)

Discussion. - Sando and Bamber (1985) considered *Amplexocarinia* a rare coral with a short stratigraphic range restricted to coral zones 1B, 1C, and 11A, a time equivalent to the deposition of the lower part of the Lodgepole Limestone in Montana. Sando (1960, p. 166) found *Amplexocarinia* only in the Lodgepole in the Williston Basin of Montana. The current study records a higher stratigraphic occurrence of *Amplexocarinia;* three specimens were found in the upper Mission Canyon (upper half of the Frobisher-Alida).

Amplexocarinia sp.
Figure 4.5 - 7

Specimens of *Amplexocarinia* in the Williston Basin are few and poorly preserved. No named species of *Amplexocarinia* have been described from the Mississippian of the Western Interior Province (Sando and Bamber, 1985).

A total of six specimens of *Amplexocarinia* were found during this study; five specimens that could be measured range from 2.5 to 7.0 mm in diameter. Specimens with a diameter between 4 and 7 mm have 18 septa. The septa are radially arranged, short, and are axially confluent with a well-developed aulos. Minor septa and dissepiments are absent.

Occurrence. - Three specimens are from the lower Bottineau interval in NDGS Well No. 607 at 10,495 to 10,500 feet below KB, and three specimens are from the upper Mission Canyon (upper Frobisher-Alida) in NDGS Well Nos. 480 and 7207, McKenzie and Williams Counties, North Dakota.

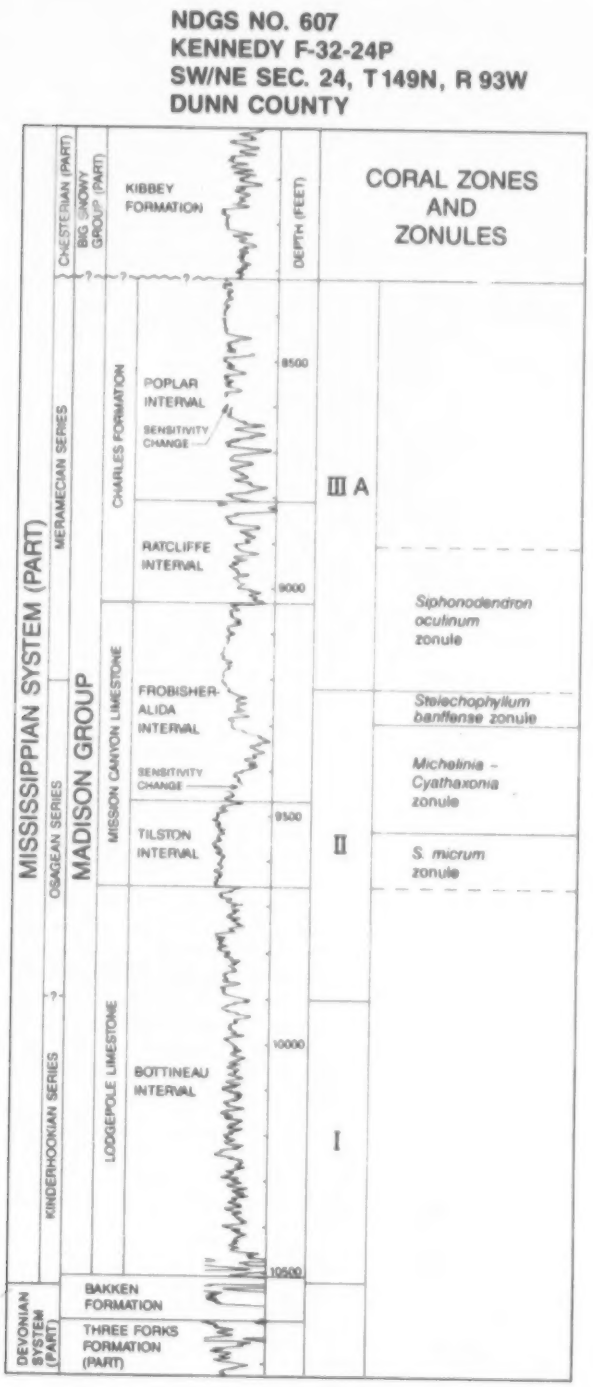


Fig. 2 Typical gamma-ray log response for strata of the Madison Group in west-central North Dakota, showing informal marker-defined interval boundaries, formal rock units, ages, coral zones of Sando and Bamber (1979, and 1985) (left column), and coral zonules recognized in this study.

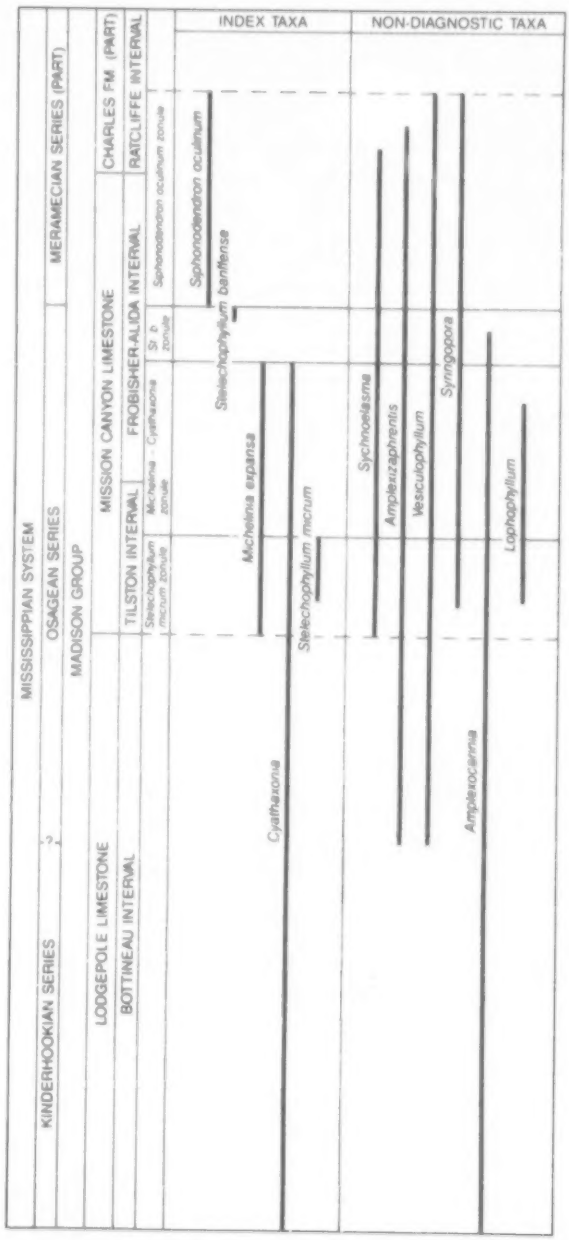


Fig. 3 Composite ranges of coral taxa and coral zonules defined by ranges of diagnostic taxa within the Mission Canyon Limestone and the lower part of the Charles Formation in the North Dakota part of the Williston Basin.

Suborder Stereolasmatina Hill, 1981

Family Hapsiphyllidae Grabau, 1928

Subfamily Hapsiphyllinae Grabau, 1928

Genus *Amplexizaphrentis* Vaughan, 1906

Zaphrentites Hudson, 1941, p. 309.

Triplophyllites Easton, 1944, p. 35.

Enniskillenia Kabakovich, 1962, p. 323.

Type Species. - *Zaphrentis curvulena* Thompson, 1881.

Diagnosis. - Small, ceratoid or trochoid rugose corals having large cardinal fossula bounded peripherally by lateral septa and axially by wall formed of fused ends of rhopaloid septa from counter quadrants; cardinal fossula ordinarily on concave side, typically expanded adaxially, but may be parallel-sided or axially constricted. Alar pseudofossulae commonly well developed. Septal plan normally pinnate, but in later growth stages septa may be withdrawn from axis and assume radial plan. Minor septa absent or poorly developed. Cardinal septum long in early stages, shortened later. Tabulae arched or flattened axially descending steeply toward periphery. No dissepiments. (From Sando and Bamber, 1985.)

Discussion. - Sando and Bamber (1985) discussed the common occurrence of *Amplexizaphrentis* throughout the Mississippian of the Western Interior Province. *Amplexizaphrentis* has a similar long range in the Williston Basin of North Dakota. At least 17 per cent of the coral fauna consists of specimens of *Amplexizaphrentis*.

Amplexizaphrentis sp.
Figure 4.8 - 10

Because the nominal species of *Amplexizaphrentis* in the Western Interior Province are in need of restudy (Sando and Bamber, 1985), it is inappropriate to make a specific assignment to specimens from the Williston Basin.

Typical specimens of *Amplexizaphrentis* in this study have 15 septa at a diameter of 3 mm, 16 to 20 septa at a diameter between 4 and 6 mm, and 26 to 27 septa at a diameter between 7 and 9 mm. A "key-hole"-shaped cardinal fossula and alar pseudofossulae are well developed in specimens 3 mm in diameter (probably representing immature specimens), and remain prominent throughout ontogeny. The cardinal septum is long in early growth stages and becomes progressively shorter during ontogeny. Other major septa are pinnate. Minor septa are absent.

Occurrence. - Only a few specimens of *Amplexizaphrentis* sp. were observed in the upper part of the Bottineau interval in NDGS Well No. 38 at 5,045 feet below KB, and in NDGS Well No. 274 at 3,102 feet below KB and 3,305 feet below KB. *Amplexizaphrentis* sp. is quite common in the Tilston and Frobisher-Alida intervals, and in the lower half of the Ratcliffe interval.

Family Zaphrentoididae Schindewolf, 1938

Subfamily Zaphrentoidinae Schindewolf, 1938

Genus *Sychnoelasma* Lang, Smith and Thomas, 1940

Homalophyllites Easton, 1944, p. 42.

Type species. - *Verneuilia urbanowitschi* Stuckenberg, 1895.

Diagnosis. - Ceratoid-trochoid, rugose corals having slit-shaped or parallel-sided cardinal fossula on convex side of corallum. Major septa long, radially arranged, fused adaxially to form axial stereozone. Minor septa long, fused with major septa abaxially forming peripheral stereozone. Tabulae arched upwards. No dissepiments. (From Sando and Bamber, 1985.)

Discussion. - *Sychnoelasma* is a common coral in the Mission Canyon Formation and lowermost Charles Formation of North Dakota, comprising 18 per cent of the total Madison coral fauna. Sando and Bamber (1985) also found this genus to be one of the more common corals in the Mississippian of the Western Interior Province, primarily restricted to coral Zone II. They mentioned that it occurs in lithofacies deposited in both shallow and deep water. A broad environmental tolerance was also observed for *Sychnoelasma* in North Dakota; it occurs with *Vesiculophyllum* and *Syringopora* in rocks representing shallow-water environments and also with the same genera in rocks representing somewhat deeper water environments.

Sychnoelasma sp.
Figure 4.11 - 13

A considerable amount of variation in shape of the fossula, development of the axial stereozone, and arrangement and shape of the septa was observed in specimens of *Sychnoelasma* from the Williston Basin of North Dakota. Specimens with a diameter of 6 mm have 26 to 27 major septa. Specimens with a diameter between 8 and 16 mm have 26 to 27 major septa. Specimens with a diameter between 8 and 16 mm have 29 to 45 major septa. *Sychnoelasma* usually has a parallel-sided fossula, but a slight flaring or tapering of the fossula adaxially was noted in some specimens. Different degrees of dilation of major septa in some specimens produced variations in the size and shape of the axial stereozone. In some specimens the ends of the major septa swirl slightly at the axis of the corallum. Minor septa are one-fourth to one-fifth as long as major septa and are fused with them to form the peripheral stereozone.

In spite of the morphologic differences noted, no consistent pattern that could be construed as species differences was observed. Although it is possible that several species are embraced herein, it is more expedient to recognize only a single variable group.

Occurrence. - Several specimens of *Sychnoelasma* sp. were found at the top of the Bottineau interval near the Bottineau-Tilston contact in NDGS Well No. 6230. *Sychnoelasma* sp. is rather common in rocks formed in more open-marine environments in the Tilston and Frobisher-Alida intervals and in the lower half of the Ratcliffe interval.

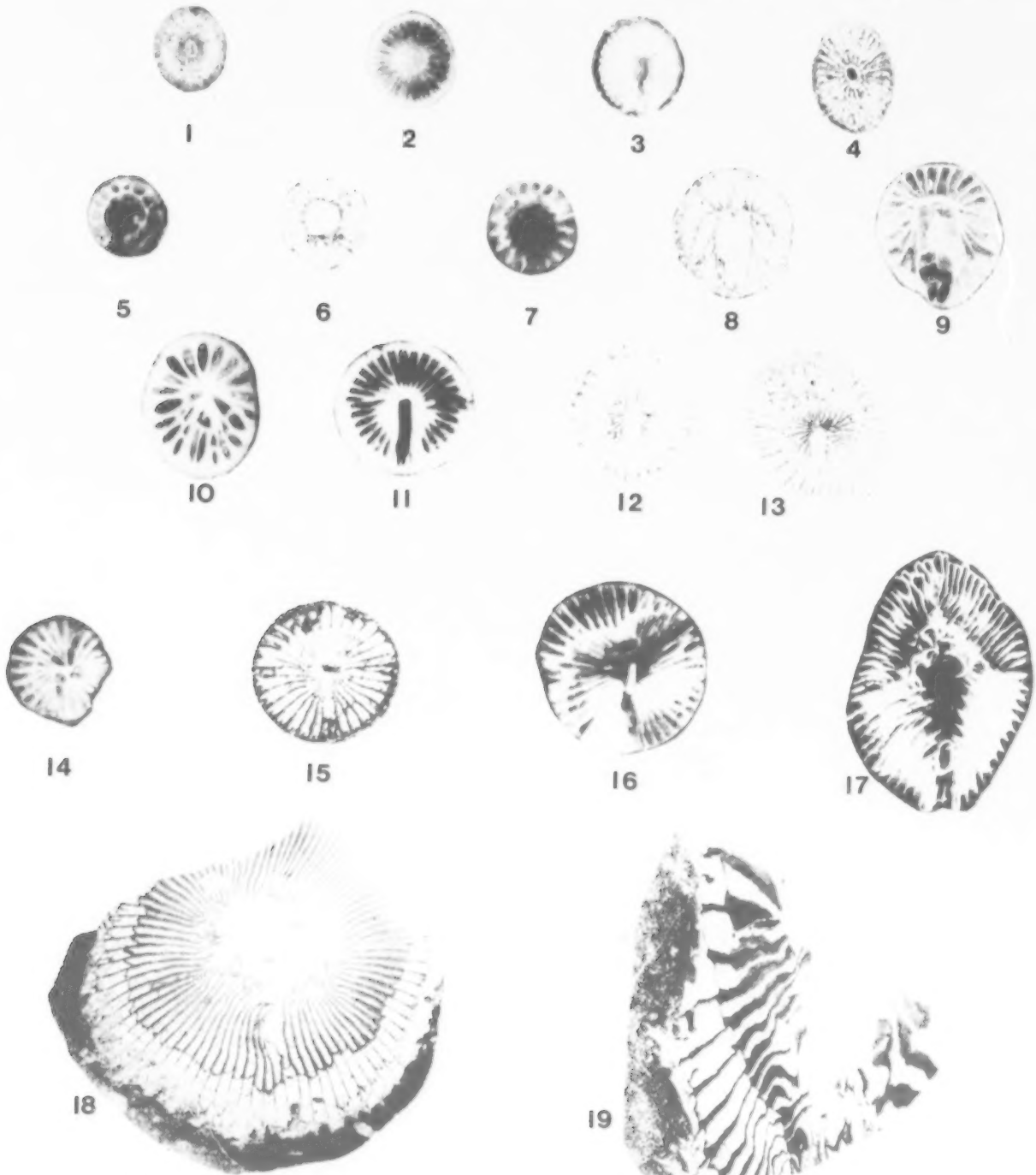


Fig. 4 1-4, *Cyathaxonia* sp. 1) transverse thin section, UND 4200., x3, Frobisher-Alida interval, NDGS Well No. 7207 at 9,691 feet below KB. 2) transverse section, polished core plug, UND 4201., x4, Frobisher-Alida interval, NDGS Well No. 7207 at 9,735 feet below KB. 3) transverse section, polished core plug, UND 4202., x4, Frobisher-Alida interval., NDGS Well No. 607 at 9,414 feet below KB. 4) transverse thin section, UND 4203., x4, Frobisher-Alida interval., NDGS Well No. 7207 at 9,756 feet below KB. 5-7, *Amplexocarinia* sp. 5) transverse section, polished slab, UND 4204., x5.6, Bottineau interval, NDGS Well No. 607 at 10,498 feet below KB. 6) transverse thin section, UND 4205., x4, Frobisher-Alida interval, NDGS Well No. 7207 at 9,586 feet below KB. 7) transverse section, polished core plug, UND 4206., x2.3, Bottineau interval NDGS Well No. 607 at 10,500 feet below KB. 8-10, *Amplexizaphrentis* sp. 8) transverse thin section, UND 4207., x3, Frobisher-Alida interval, NDGS Well No. 480 at 8,731 feet below KB. 9) transverse section, polished core piece, UND 4208., x2.5, Ratcliffe interval, NDGS Well NO. 2667 at 9,485 feet below KB. 10) transverse section, polished core plug, UND 4209., x4, Frobisher-Alida, NDGS Well No. 7207 at 9,549 feet below KB. 11-13, *Sychnoelasma* sp. 11) transverse section, polished core plug, UND 4210., x2.8, Ratcliffe interval., NDGS Well No. 2667 at 9,483 feet below KB. 12) transverse thin section, UND 4211., x3, Frobisher-Alida interval, NDGS Well No. 7307 at 9,526 feet below KB. 13) transverse thin section, UND 4212., x3, Tilston interval, NDGS Well No. 511 at 8,093 feet below KB. 14-16, *Lophophyllum* sp. 14) transverse section, polished core plug, UND 4213., x3, Frobisher-Alida interval, NDGS Well No. 1350 at 9,210 feet below KB. 15) transverse thin section, UND 4214., x3, Tilston interval, NDGS Well No. 6230 at 10,102 feet below KB. 16) transverse section, polished core slab, UND 4215., x2, Frobisher-Alida interval, NDGS Well No. 607 at 9,378 feet below KB. 17-19 *Vesiculophyllum* sp. 17) transverse section, polished core slab, UND 4216., x1, Ratcliffe interval, NDGS Well No. 7207 at 9,366 below KB. 18) transverse thin section, UND 4217., x1, Frobisher-Alida interval, NDGS Well No. 1024 at 7,155 to 7,214 feet below KB. 19) longitudinal section, thin section, UND 4217., x1, same specimen as 18.

Suborder Plerophyllina Sokolov, 1960

Family Lophophyllidae Grabau, 1928

Genus *Lophophyllum* Milne-Edwards and Haime, 1850

Type species. - *Lophophyllum konincki* Milne-Edwards and Haime, 1850.

Diagnosis. - Trochoid, rugose corals having prominent cardinal fossula on convex side of corallum. Columella simple, styliform. Major septa long, pinnate to radial in plan, may or may not extend to columella. Minor septa short. Tabulae arched upward adaxially. Dissepiments absent or poorly developed in mature stage only. (From Sando and Bamber, 1985.)

Discussion. - Although the type species of *Lophophyllum* is in need of further study (Sando and Bamber, 1985), specimens in this study are here assigned to this genus pending a complete generic revision.

Lophophyllum sp.
Figure 4.14 - 16

Because of the taxonomic uncertainty of *Lophophyllum* and the probability that several species of this genus in the Western Interior Province are synonyms (Sando and Bamber,1985), it is impracticable to assign the Williston Basin specimens to any particular species of *Lophophyllum*.

Specimens in the Williston Basin have 24 major septa at a diameter of 6 mm, 33 major septa at a diameter of 10 mm, and 43 major septa at a diameter of 14 mm. The cardinal fossula is positioned to one side of the plane of bilateral symmetry. Specimens are characterized by a blade-like columella that has its long axis variably oriented within the corallum. Major septa of several specimens appear to swirl toward the columella (Figure 4.14-16), and are usually in contact with it. Minor septa are short. Dissepiments are incomplete or absent.

Occurrence. - Only a few specimens of *Lophophyllum* sp. were found in lithologies representing more open-marine depositional environments in the lower part of the Mission Canyon Limestone (Tilston interval and lower part of the Frobisher-Alida interval).

Suborder Caniniina Wang, 1950

Family Uraliniidae Dobrolyubova, 1962

Genus *Vesiculophyllum* Easton, 1944

Kakwiphyllum Sutherland, 1954, p. 365.

Type species. - *Chonophyllum sedaliense* White, 1880.

Diagnosis. - Large, cylindrical, rugose corals having numerous major septa that closely approach axis but may be short, leaving open area in axial region. Bilateral, palmate, or radial septal plan. Cardinal septum long or short and may or may not be in a fossula. Counter septum usually short. Septa ordinarily dilated, confined to axial region in later growth stages. Minor septa absent or short and impersistent. Dissepimentarium broad, lonsdaleoid; inner zone of regular dissepiments present. Numerous incomplete tabulae steeply inclined adaxially, or bowl-shaped, gradational with dissepiments. (From Sando and Bamber, 1985.)

Discussion. - Sando (1969, p. 301) observed that some specimens of *Vesiculophyllum* have septa that withdraw from the center of the corallum, and he referred to these forms as enygmophylloid variants because of their close morphologic similarity to the genus *Enygmophyllum*.

Vesiculophyllum sp.
Figures 4.17 - 19, 5.1 - 3

Extreme ontogenetic and individual variation of specimens referred to the genus *Vesiculophyllum* cause such great difficulty in discrimination of species that the number of species in the Western Interior Province is unknown (Sando and Bamber, 1985). Specimens from the Williston Basin also show extreme morphologic variation and thus were assigned to *Vesiculophyllum* sp., realizing that several species might be present. *Vesiculophyllum*, the most abundant coral in the Madison of North Dakota, makes up 45 per cent of the total coral fauna. It ranges throughout most of the Madison in North Dakota and it has a broad environmental tolerance spanning the intertidal to open-marine depositional environments.

Vesiculophyllum is the largest Mississippian solitary rugosan in the Williston Basin of North Dakota. Specimens have 41 to 52 major septa at a diameter between 12 and 30 mm, and 52 to 63 major septa at a diameter between 30 and 44 mm. The largest specimen (Figure 4.18, 19) measured 63 mm in diameter and has 87 major septa. Several specimens measured 50 to 130 mm in length, with the coralla cylindrical to slightly ceratoid. Major septa are dilated adaxially, and some specimens have major septa that withdraw form the axis of the corallum (Figure 4.17, enygmophylloid variant). Minor septa were not observed. A cardinal fossula having a shortened cardinal septum was observed in several specimens. The outer zone of dissepiments (considered structurally weak by Sando, 1960b, p. 180) of most specimens has been eroded away. The tabulae of most specimens are incomplete and steeply inclined toward the axis of the corallum (Figure 5.2), although in several specimens the tabulae are flattened or somewhat horizontal.

Occurrence. - Only a few specimens of *Vesiculophyllum* sp. were found in the Bottineau interval in NDGS Well No. 38 at 5,035 to 5,036 feet below KB and in NDGS Well No. 274 at 3,143 feet below KB. *Vesiculophyllum* sp. is widespread in the Tilston, Frobisher-Alida, and Ratcliffe intervals.

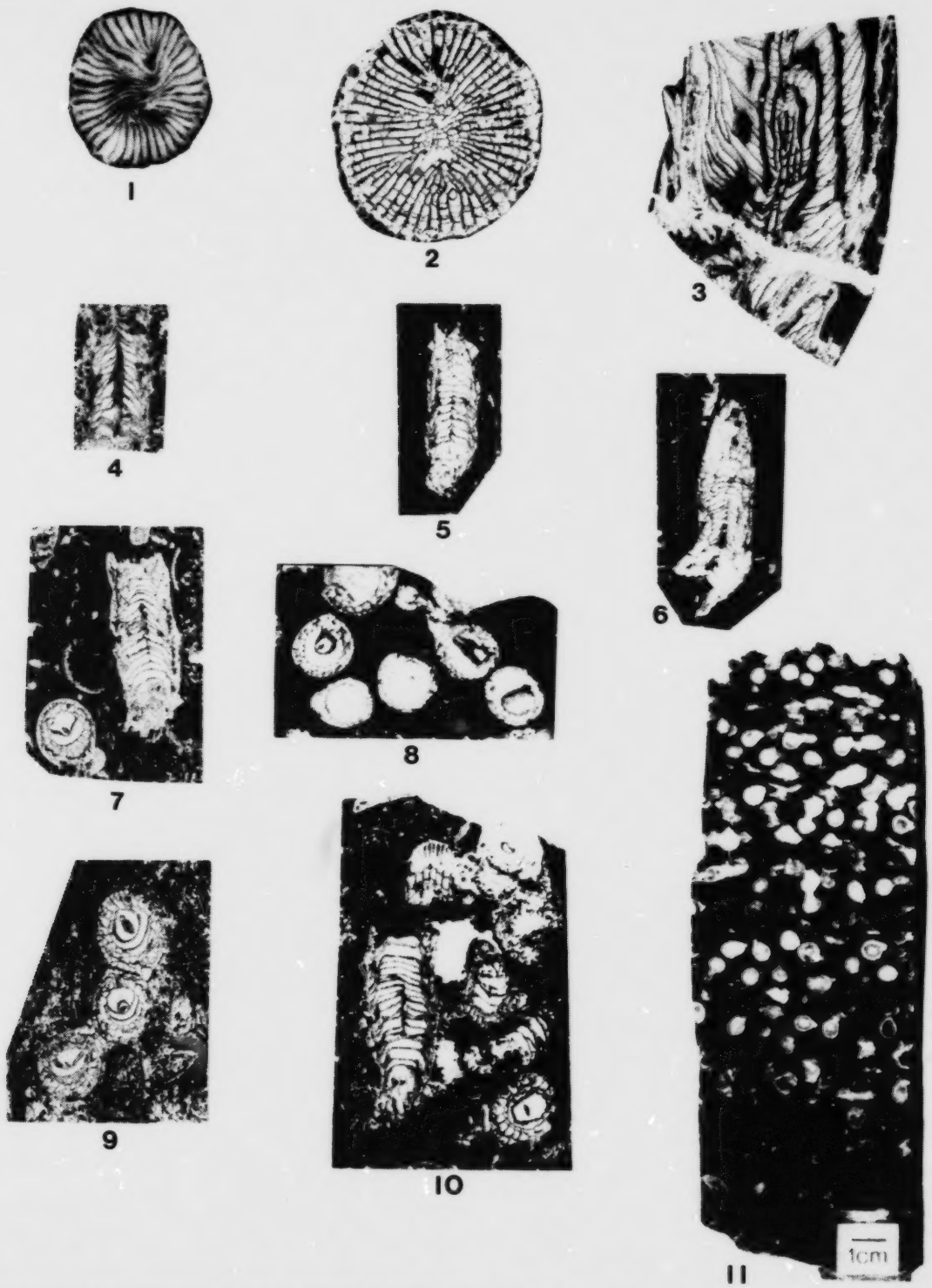


Fig. 5 1-3, *Vesiculophyllum* sp. 1) transverse section, polished slab, UND 4218., x2, Frobisher-Alida interval, NDGS Well No. 607 at 9,290 feet below KB. 2) transverse thin section, UND 4219., x2, Frobisher-Alida interval, NDGS Well No. 480 at 8,691 feet below KB. 3) longitudinal thin section, UND 4219., x2, same as specimen 2. 4-11, *Siphonodendron oculinum* (Sando). 4) longitudinal thin section, UND 4220., x2, Ratcliffe interval, NDGS Well No. 4455 at 9,252 feet below KB. 5) longitudinal thin section, UND 4221., x2, Frobisher-Alida interval, NDGS Well No. 7207 at 9,520 feet below KB. 6) longitudinal thin section, UND 4222., x2, Ratcliffe interval, NDGS Well No. 7207 at 9,394 feet below KB. 7) longitudinal and transverse thin sections, UND 4223., x2, Ratcliffe interval, NDGS Well No. 2667 at 9,469 feet below KB. 8) transverse thin section, UND 4224., x2, Ratcliffe interval, NDGS Well No. 4455 at 9,251 feet below KB. 9) transverse thin section, UND 4220., x2, Ratcliffe interval, NDGS Well No. 4455 at 9,252 feet below KB. 10) longitudinal and transverse thin sections, UND 4220., x2, Ratcliffe interval, NDGS Well No. 4455 at 9,252 feet below KB. 11) transverse sections, polished core slab, UND 4224., scale as indicated, Ratcliffe interval NDGS Well No. 4455 at 9,251 feet below KB.

Suborder Lithostrotionina Spasskiy and Kachanov, 1971

Family Lithostrotionidae d'Orbigny, 1852

Subfamily Lithostrotioninae d'Orbigny, 1852

Genus *Siphonodendron* McCoy, 1849

Cystidendron Schindewolf, 1927, p. 149.

Type species. - *Siphonodendron aggregatum* McCoy, 1851.

Diagnosis. - Phaceloid, columella simple, styliform. Major septa commonly long, may extend to the columella. Minor septa short. Tabulae large, tent-shaped, commonly supplemented by outer, smaller, nearly horizontal tabulae. Dissepimentarium regular, continuous, wide in larger species but narrow and discontinous in small species. (From Sando and Bamber, 1985.)

Discussion. - The genus *Diphyphyllum* is very similar to *Siphonodendron* , except that it has flat tabulae and is noncolumellate. The validity of *Diphyphyllum* as a distinct genus has been questioned by several workers (Sando and Bamber, 1985).

Siphonodendron oculinum (Sando, 1963)
Figure 5.4 - 11

Lithostrotion (Siphonodendron) sp. Sando, 1960, p. 183, pl. 19, figs. 7-12.

Lithostrotion (Siphonodendron) oculinum Sando, 1963, p. 1075, pl. 145, fig. 105.

Diagnosis. - Phaceloid coralla, corallites small, 4 to 6 mm in diameter, having 20 to 25 major septa that extend one third to one half the radius of the corallite; minor septa present, half as long as major septa. Columella ordinarily continuous but may be impersistent. Tabulae tent-shaped, strongly deflected near periphery of tabularium; where columella not well developed, tabulae are flattened. Single row of dissepiments present. (Slightly modifed and abbreviated from Sando, 1963.)

Discussion. - Several colonies of *Siphonodendron oculinum* in the Williston Basin of North Dakota have both siphonodendroid and diphyphylloid corallites in the same corallum; however, siphonodendroid corallites tend to dominate (see also Sando, 1960, p. 183; 1963, p.1075). Corallites are 4.5 to 5.5 mm in diameter (average diameter 5 mm). Corallites that have a diameter of 5 mm have 19 to 20 major septa that are half the radius. Minor septa are half as long as major septa. Columella is bladelike and is impersistent in some corallites. The tabulae are tent-shaped and strongly deflected toward the periphery. In some specimens the tabulae are so strongly deflected toward the periphery that they rest upon the underlying tabula. Where this occurs, a short horizontal accessory tabula is present and extends from the deflected edge of the tabula to the periphery of the corallite.

Occurrence. - *Siphonodendron oculinum*, a Meramecian coral, is relatively rare in North Dakota. It is restricted to an area west of the Nesson Anticline in lithologies representing more open-marine conditions. *Siphonodendron oculinum* occurs in the upper half of the Frobisher-Alida interval and lower half of the Ratcliffe interval and is a zonule index.

Subfamily Acrocyathinae Hill, 1981

Genus *Stelechophyllum* Tolmachev, 1933

Lithostrotionella Yabe and Hayasaka. Hayasaka, 1936, p. 61, 62, 64, 65, 67, 68 (part).

Stelechophyllum Tolmachev. Sando, 1983, p. 9 (see for further synonomy).

Type species. - *Stylophyllum venukofi* Tolmachev, 1924.

Diagnosis. - Cerioid rugosan, major septa thin, ordinarily extending across tabularium to columella but discontinuous or absent in dissepimentarium. Minor septa poorly developed or absent. Columella ordinarily a simple axial rod or plate that may be derived from one or more major septa. Tabularium consisting of axial series of tent-shaped, complete tabulae resting one upon the other and a weak peripheral series of horizontal or inclined concave-upward tabellae. Dissepimentarium lonsdaleoid. (From Sando and Bamber, 1985.)

Discussion. - The genus *Thysanophyllum* is very similar to *Stelechophyllum* but the former lacks a columella or has a poorly developed and impersistent columella and flat or sagging tubulae. The taxonomic validity of *Thysanophyllum* is uncertain at this time (Sando and Bamber, 1985).

Stelechophyllum banffense (Warren, 1927)
Figure 6

Lithostrotion banffense (Warren). Sando, 1983, p. 13 (see for further synonomy), pl. 3; pl. 4, figs. 1, 2.

Diagnosis. - Corallite diameter 6 to 13 mm, with 19 to 26 major septa, variable in length, rarely joining columella or extending into dissepimentarium. Minor septa very small, poorly developed, or absent. Columella present or poorly developed. Dissepimentarium lonsdaleoid, composed of one to six rows of inflated and variably sized dissepiments; more than one row of dissepiments usually present. Axial tabulae tent-shaped; tabulae strongly deflected downward toward periphery; where columella is poorly developed tabulae are flattened. Peripheral tabellae present or poorly developed. (Slightly modified from Sando, 1983.)

Discussion. - Several colonies of *Stelechophyllum banffense* in the Williston Basin of North Dakota have both stelechophylloid and thysanophylloid corallites, but stelechophylloid corallites always predominate. Corallite diameters are between 6 and 12 mm (10 mm average). Specimens having a corallite diameter of 10 mm possess 20 to 24 major septa. Major septa rarely extend to the columella. Minor septa are short, poorly developed, or absent. The columella is styliform and may be impersistent. In some specimens the columella is absent (Figure 6.3). Axial tabulae are tent-shaped. Peripheral tabellae are poorly to well-developed. When present, tabellae are slightly concave to straight and deflected downward from the shoulders of the tabulae to the periphery of the corallite. The dissepimentarium is composed of 2 to 5 rows of small to large, inflated dissepiments.

Stelechophyllum banffense is a zonule index coral that can be distinguished from *Stelechophyllum micrum*, index species of the lowest zonule, by its larger corallites (*S. banffense* has an average corallite diameter of 10 mm, as opposed to *S. micrum* which has a corallite diameter between 3 and 4 mm), greater number of major septa (*S. banffense* has 20 to 24 major septa, *S. micrum* has 15 to 16 major septa), and poorly developed or lack of minor septa (minor septa of *S. micrum* are usually well-developed).

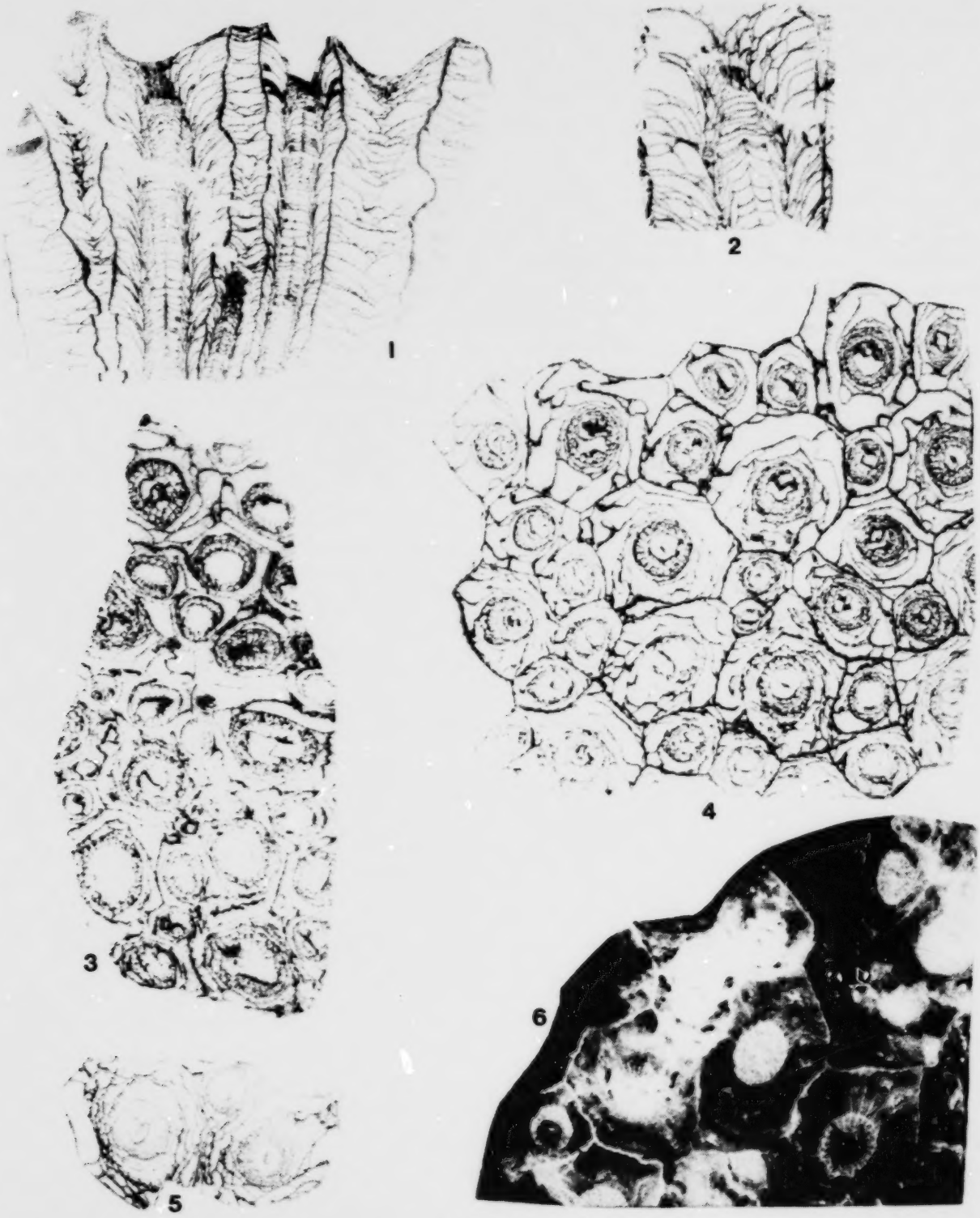


Fig. 6 1-6, *Sutiechophyllum banffense* (Warren). 1) longitudinal thin section, UND 4225., x2, Frobisher-Alida interval, NDGS Well No. 480 at 8,733 feet below KB. 2) longitudinal thin section, UND 4226., x2, Frobisher-Alida interval, NDGS Well No. 5258 at 9,330 feet below KB. 3) transverse thin section, UND 4227., x2, Frobisher-Alida interval, NDGS Well No. 7446 at 9,359 feet below KB. 4) transverse thin section, UND 4225., x2, Frobisher-Alida interval, NDGS Well No. 480 at 8,733 feet below KB. 5) transverse thin section, UND 4226., x2, Frobisher-Alida interval, NDGS Well No. 5258 at 9,330 feet below KB. 6) transverse section, core piece, UND 4226., x2, Frobisher-Alida interval, NDGS Well No. 5258 at 9,330 feet below KB.

Stelechophyllum banffense is quite rare and this study records the first definite occurrence of this species in the conterminous United States. The type material of *S. banffense* (Warren) was believed to have been derived from the lower Mount Head Formation of early Meramecian age (Nelson, 1960, p. 119). We place the boundary between the Meramecian and Osagean in the Williston Basin at the last occurrence of *Stelechophyllum banffense* because it appears to be contiguous with the first occurrence of *Siphonodendron oculinum* (which is regionally where the boundary is placed, according to Sando and Bamber, 1985); however, *S. banffense* has a much more consistent stratigraphic position than *Siphonodendron oculinum*. Armstrong (1970a, 1970b, 1975) studied *S. banffense* in Alaska where it ranges throughout most of the Meramecian.

Occurrence. - *Stelechophyllum banffense* has a very short stratigraphic range in North Dakota (15-20 feet) and is an excellent biostratigraphic marker. The occurrence of *Stelechophyllum banffense* in the Mission Canyon of the Williston Basin represents the earliest recorded occurrence of this species in North America. In North Dakota, *S. banffense* is restricted to an area west of the Nesson Anticline and is found in rocks indicative of restricted- to open-marine conditions. Its occurrence exclusively in the upper half of the Frobisher-Alida interval is the basis of the thin *S. banffense* zonule. Occurrences not shown in Waters and Sando (in press) are in NDGS Well No. 4683 (Golden Valley County), 9,191 feet below KB and in NDGS Well No. 5639 (Dunn County), 9,453 to 9,473 feet below KB.

Stelechophyllum micrum (Kelly, 1942)
Figure 7.1 - 5

Lithostrotionella micra Kelly, 1942, p. 357, pl. 50, fig. 7.

Stelechophyllum micrum (Kelly). Sando, 1983, p. 13 (see for further synonomy).

Diagnosis. - Corallites 2 to 6 mm in diameter having 10 to 15 major septa that extend from columella toward dissepimentarium but ordinarily not through it. Minor septa small, poorly developed. Columella commonly well developed. Dissepimentarium composed of 1 to 2 rows of inflated dissepiments. Axial tabulae tent-shaped. Peripheral tabellae poorly developed. (Slightly modified from Sando, 1983.)

Discussion. - Only five colonies were collected from four wells in this study. Silicified specimens from the more open-marine lithologies (Figure 7.2) are smaller (corallite diameters 3 to 4 mm), and are not as well preserved as the single specimen in the shallower intertidal lithology (Figure 7.1, 3, 5). Specimens having corallite diameters of 3 to 4 mm have 13 major septa. A specimen having a corallite diameter of 5 mm has 15 to 16 major septa. Major septa extend from the columella to the dissepimentarium. Minor septa are ordinarily present and are one half to one third as long as major septa. The columella is usually well developed but may be impersistent. Axial tabulae are tent-shaped, but peripheral tabellae were not observed. Specimens have two rows of inflated dissepiments.

Stelechophyllum micrum, which defines a relatively thin coral zonule in the Tilston interval, differs from *Stelechophyllum banffense*, which defines a thin coral zonule in the upper part of the Frobisher-Alida interval, by being smaller, having fewer major septa, and having better developed minor septa. In addition, the major septa of *S. micrum* are ordinarily in contact with the columella.

This is the first record of *Stelechophyllum micrum* in the United States. *S. micrum* has a short stratigraphic range in the Williston Basin of North Dakota but has a broad environmental tolerance; it occurs in peloidal-pseudoolitic packstone or grainstone of the intertidal environment and in skeletal wackestone of the somewhat deeper open-marine environment. *S. micrum* has been reported from the lower Shunda and upper Pekisko Formations of the Rocky Mountains of southern British Columbia and Alberta (Bamber, 1966, p.14) and the Tilston interval of southeastern Saskatchewan (Brindle, 1960, p.43).

Occurrence. - *Stelechophyllum micrum* occurs exclusively in the lower half of the Tilston interval, where it defines the lowest coral zonule (*S. micrum* zonule) recognized in this study.

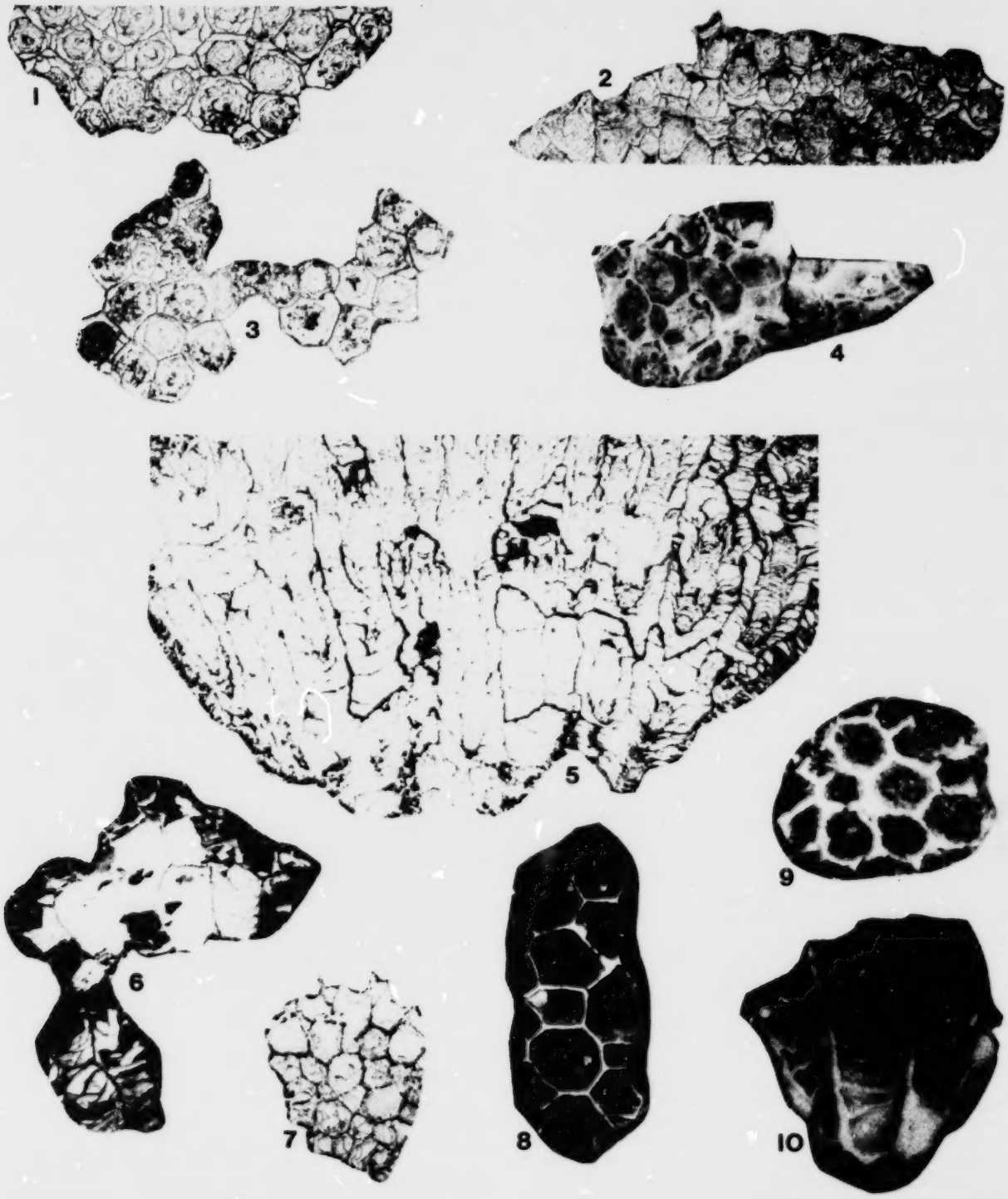


Fig. 7 1-5, *Stelechophyllum micrum* (Kelly). 1) transverse thin section, UND 4228., x2, Tilston interval, NDGS Well No. 511 at 8,034 feet below KB. 2) transverse thin section, UND 4229., x2, Tilston interval, NDGS Well No. 6230 at 10,135 feet below KB. 3) transverse thin section, UND 4228., x2, Tilston interval, NDGS Well No. 511 at 8,034 feet below KB. 4) transverse section, polished core piece, UND 4230., x2, Tilston interval, NDGS Well No. 38 at 4,597 feet below KB. 5) longitudinal thin section, UND 4228., x2, Tilston interval, NDGS Well No. 511 at 8,034 feet below KB. 6-10, *Michelinia expansa* (White). 6) longitudinal thin section, UND 4231., x1, Frobisher-Alida interval, NDGS Well No. 6230 at 9,888 feet below KB. 7) transverse thin section, UND 4232., x1, Tilston interval, NDGS Well No. 6230 at 10,173 feet below KB. 8) transverse section, polished core slab, UND 4233., x2, Frobisher-Alida, NDGS Well No. 7207 at 9,678 feet below KB. 9) transverse section, polished core piece, UND 4234., x2, Tilston interval, NDGS Well No. 38 at 4,578 feet below KB. 10) longitudinal section, polished core slab, UND 4235., x2, Frobisher-Alida interval, NDGS Well No. 7207 at 9,683 feet below KB.

Subclass Tabulata Milne-Edwards and Haime, 1850

Order Favositida Wedekind, 1937

Suborder Favositina Wedekind, 1937

Superfamily Favositicae Dana, 1847

Family Michelinliidae Waagen and Wentzel, 1886

Subfamily Michelininae Waagen and Wentzel, 1886

Genus *Michelinia* de Koninck, 1841

Conopoterium Winchell, 1865, p. 110.

Type species. - *Calamopora tennuiseptata* Phillips, 1836.

Diagnosis. - Cerioid tabulate corals of variable corallum shape. Walls pierced by mural pores. Septal spines or ridges present. Tabulae numerous, incomplete, convex. (From Sando and Bamber, 1985.)

Discussion. - Some coral students (Lang and others, 1940, p. 85, 103; Easton, 1944, p. 55) treated *Michelinia* as a junior subjective synonym of *Pleurodictyum*, whereas others (Nelson, 1962, p. 955; Sando, 1969, p. 311; Hill, 1981, p. 561, 565) considered the two as distinct genera. We agree with the latter authors that *Michelinia* and *Pleurodictyum* are distinct; the major differences between the two genera are the completeness of tabulae (*Michelinia* has incomplete tabulae and *Pleurodictyum* has complete tabulae) and the shape of the corallum (*Michelinia* commonly has a conical corallum, whereas *Pleurodictyum* has a discoidal corallum).

Michelinia expansa (White, 1880)
Figure 7.6 - 10

Michilinia expansa White, 1880, p. 158, pl. 39, fig. 2a, b (advanced printing); 1883, p. 158, pl. 39, fig. 2a, b.

Pleurodictyum expansum (White) Easton, 1944, p. 55, pl. 13, fig. 9, pl. 17, fig. 2; Easton and Gutschick, 1953, p. 24, pl. 1, fig. 6; Nelson, 1962, p. 955, pl. 137, figs, 1-6, t. - figs. 1a, b, 2a-c.

Michelinia expansa (White) Bowsher, 1961, pl. 109, fig. 4; Sando, 1969, p. 311, pl. 39, figs. 1-3.

Diagnosis. - Discoidal to conical coralla; corallites quadrangular, pentagonal, hexagonal, or septagonal; most commonly hexagonal; corallite diameter 6 to 12 mm averaging 7 mm. Tabulae numerous, usually incomplete, flat, sagging, or convex, small and convex along peripheral part of corallite. (Modified from Sando, 1969, p. 311.)

Discussion. - Coralla of *Michelinia expansa* in the Williston Basin of North Dakota are conical to broadly conical (Figure 7.10), and are 30 to 98 mm in length from the apex of the corallum to the upper surface of the corallum. Corallites are usually hexagonal or septagonal and are 5 to 12 mm in diameter. Average corallite diameters are 6 to 7 mm. Tabulae are incomplete and convex along the periphery of the corallite and infundibular in the center of the corallite.

Specimens identified as *Michelinia expansa* from the Williston Basin of North Dakota are considered to be conspecific with the specimen figured and assigned to *Michelinia expansa* by Bowsher (1961, pl. 109, fig. 4). The presence of this species in older Mississippian rocks (late Kinderhookian to early Osagean in age) of the Southeastern Coral Province indicates that this species had a long geologic range and wide geographic distribution.

The stratigraphic range of *M. expansa* in North Dakota is very similar to the regional range of the species recognized by Sando and Bamber (1985); however, it may be slightly more abundant stratigraphically higher in the section in the Williston Basin than in correlative rock units regionally.

Occurrence. - *M. expansa* occurs with *Cyathaxonia* in rocks representing more open marine conditions in the Tilston and lower half of the Frobisher-Alida interval.

Order Auloporida Sokolov, 1947

Superfamily Syringoporicae de Fromentel, 1861

Family Syringoporidae de Fromentel, 1861

Genus *Syringopora* Goldfuss, 1826

Harmodites Fischer von Waldheim, 1828, p. 19.

Type Species. - *Syringopora ramulosa* Milne-Edwards and Haime, 1850.

Diagnosis. - Phaceloid tabulate corals having corallites connected by randomly arranged tubules. Tabulae central or subcentral; corallites nearly same size within single colony; corallites 1.1 to 4.0 mm in diameter with frequency of 2 to 18 per square centimeter. Septal spines short, sporadically developed. Wall structure lamellar. (Modified from Nelson, 1977, p. 550.)

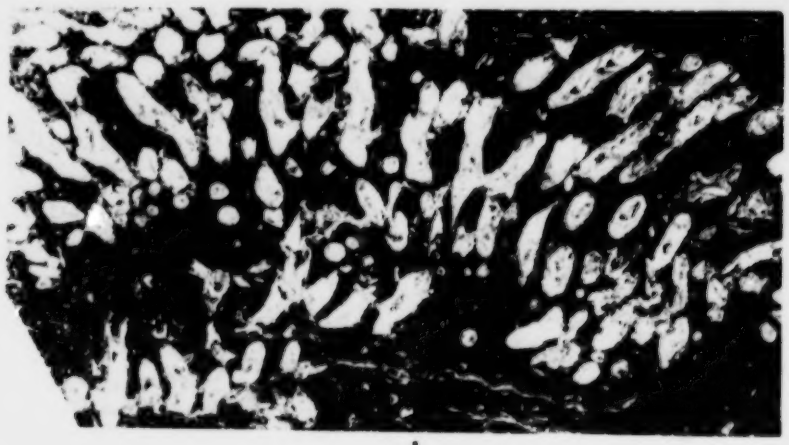
Discussion. - Sando (1984) recognized seven morphogroups (A to G) in the genus *Syringopora*. Some of these morphogroups had been previously assigned to different species by various authors and the taxonomy is not yet entirely settled. This study adopts the morphogroup concept used by Sando (1984). Four of the morphogroups (A to D) occur in the Williston Basin of North Dakota.

Syringopora sp.
Figure 8

Morphologically, Williston Basin specimens of *Syringopora* morphogroups A to D differ only in their corallite diameters and the number of corallites per square centimeter. These are: morphogroup A, diameter 1.1 to 1.8 mm, frequency 8 to 18/cm^2; morphogroup B, diameter 1.9 to 2.6 mm, frequency 3 to 14/cm^2; morphogroup C, diameter 2.7 to 3.3 mm, frequency 3 to 10/cm^2; and morphogroup D, diameter 3.5 mm, frequency 2 to 14/cm^2.

Although coralla range from phaceloid to dendroid, they are primarily dendroid (Figure 8.3). Corallites are the same size within a single colony. Visceral cavity is axial or subaxial but primarily axial (e.g. Figure 8.4). Tabulae are infundibular. Septal spines are extremely short or absent.

Occurrence. - Morphogroup B is the most abundant syringoporoid in the Williston Basin, followed by specimens from morphogroups C, A, and D, in order of decreasing abundance. Specimens of morphogroups B and C range notably higher stratigraphically than do specimens from morphogroup A, and slightly higher than representatives of morphogroup D. Individuals of morphogroups A and D also seem to have been more sensitive to marine conditions, as they occur primarily in rocks representing more open-marine environments IV and V (Waters and Sando, 1987 and in press). Morphogroups B and C on the other hand, had a greater environmental tolerance and occur in rocks that formed in shallow water environments II, through the more open-marine environment V (Waters and Sando, 1987 and in press). Specimens of *Syringopora* morphogroup B and of *Vesiculophyllum* were the only corals to inhabit some of the shallower marine environments. *Syringopora* (taken as a group of variable forms) is evenly distributed through the Tilston interval, Frobisher-Alida interval and lower half of the Ratcliffe interval, and comprises approximately 4.5 per cent of the total Madison coral fauna.

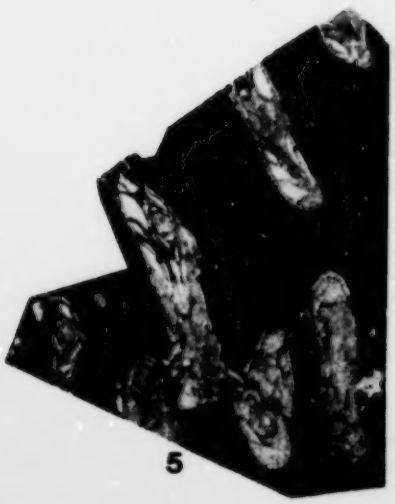


1

2

3

4



5

Fig. 8 1-5, *Syringopora* sp. 1) morphogroup B, longitudinal thin section, UND 4236., x2, Frobisher-Alida interval, NDGS Well No. 607 at 9,359 feet below KB. 2) morphogroup C, transverse thin section, UND 4237., x2, Frobisher-Alida interval, NDGS Well No. 527 at 9,951 feet below KB. 3) morphogroup D, corallum, core, UND 4238., x0.5, Frobisher-Alida interval, NDGS Well No. 4692 at 6,401 feet below KB. 4) morphogroup D, transverse thin section, UND 4239., x2, Ratcliffe interval, NDGS Well No. 3235 at 9,125 feet below KB. 5) morphogroup D, longitudinal thin section, UND 4239., x 2, same specimen as 4.

ACKNOWLEDGEMENTS

This paper is an outgrowth of a thesis submitted by D.L. Waters for the M.Sc. degree at the University of North Dakota. We thank Drs. F.D. Holland, Jr., A.M. Cvancara, and J.R. Reid of the University of North Dakota for early guidance of the project. We are also grateful to S.B. Anderson of the North Dakota Geological Survey, R.F. Lindsay of Gulf Oil Exploration and Production Company, J.C. Pol and P.K. Mescher of ARCO Exploration Company, and D.M. Petty of Tenneco Oil Exploration and Production Company for helpful discussions and suggestions during laboratory studies. Tenneco Oil Exploration and Production Company and ARCO Exploration Company provided generous grants to support the laboratory studies. The North Dakota Geological Survey provided facilities and equipment for core examination. The paper was reviewed by J.T. Dutro, Jr. and W.A. Oliver, Jr.

REFERENCES CITED

Anderson, S.B., Hansen, D.E., and Eastwood, W.P., 1960. Subsurface studies. In: Oil fields in the Burke County area, North Dakota. North Dakota Geological Survey Report of Investigations No. 36, p. 1-25.

Armstrong, A.K., 1970a. Mississippian rugose corals, Peratrovich Formation, west coast, Prince of Wales Island, southeastern Alaska. U.S. Geological Survey Professional Paper 534, 44 p.

——— 1970 b. Carbonate facies and the lithostrotionid corals of the Mississippian Kogruk Formation, Delong Mountains, northwestern Alaska. U.S. Geological Survey Professional Paper 664, 38 p.

——— 1975. Stratigraphy and paleoecology of Carboniferous corals, Lisburne Group, Brooks Range, Arctic Alaska Bulletins of American Paleontology, 67(287): 16-31.

Ballard, F.V., 1963. Structural and stratigraphic relationships in the Paleozoic rocks of eastern North Dakota. North Dakota Geological Survey Bulletin, 40, 42 p.

Bamber, E.W., 1966. Type lithostrotionid corals from the Mississippian of western Canada. Canada Geological Survey Bulletin, 135, 28 p.

Bowsher, A.L., 1961. The stratigraphic occurrence of some Lower Mississippian corals from New Mexico and Missouri. Journal of Paleontology, 34(5):955-962.

Brindle, J.E., 1960. Mississippian megafaunas in southeastern Saskatchewan. Saskatchewan Department of Mineral Resources Report No. 45, 107 p.

Carlson, C.G., and Anderson, S.B., 1966. A look at the lower and middle Madison of northwestern North Dakota. North Dakota Geological Survey Report of Investigations No. 43, 14 p.

Easton, W.H., 1944. Corals of the Chouteau and related formations of the Mississippi Valley region. Illinois State Geological Survey Report of Investigations No. 97, 93 p.

Easton, W.H., and Gutschick, R.C., 1953. Corals from the Redwall Limestone (Mississippian) of Arizona. Southern California Academy of Science Bulletin, 52, 27 p.

Eastwood, W.P., 1961. Maps of the Frobisher-Alida interval in North Dakota, North Dakota Geological Survey Report of Investigations No. 37, 3 pls.

Gutschick, R.C., and Sandberg, C.A., 1983. Mississippian continental margins of the conterminous United States. In: Stanley, D.J., and Moore, G.T., eds., The shelfbreak: Critical interface on continental margins. Society of Economic Paleontologists and Mineralogists Special Publication No. 33, p. 79-96.

Hayasaka, I., 1936. On some North American species of *Lithostrotionella*. Taihoku Imperial University, Faculty of Science and Agriculture Memoir, 13(5):47-73.

Hill, D., 1981. Rugosa and Tabulata. In: Robinson, R. A., ed., Coelenterata, Part F, Supplement 1, p. 1-762, Treatise on Invertebrate Paleontology: Boulder, Colorado, and Lawrence, Kansas, Geological Society of America and University of Kansas Press.

Hudson, R.G.S., 1941. On the Carboniferous corals: *Zaphrentis carruthersi* sp. nov. from the Mirk Fell Beds and its relation to the *Z. delanouei* species group. Yorkshire Geological Society Proceedings, 24(4):290-311.

Kabakovich, N.V., 1962. Podotryad Polycoeliina. In: Sokolov, B.S., ed., Osnovy paleontologii, v. 2, p. 324-327, Gubki, Arkheotsiaty, Kishechnopolostnye, chervi, Akademyia Nauk SSSR.

Kelly, W.A., 1942. Lithostrotionidae in the Rocky Mountains. Journal of Paleontology: 16(3):351-361.

Lang, W.D, Smith, S., and Thomas, H.D., 1940. Index of Paleozoic coral genera. British Museum (Natural History), London, 231 p.

Nelson, S.J., 1960. Mississippian lithostrotionid zones of the southern Canadian Rocky Mountains. Journal of Paleontology, 34(1):107-126.

——— 1962, Permo-Carboniferous tabulate corals from western Canada. Journal of Paleontology, 36(5):953-964.

Sando, W.J., 1960 (1961). Corals from well cores of Madison Group, Williston Basin: U.S. Geological Survey Bulletin, 1071-F:157-190.

——— 1963. New species of colonial rugose corals from the Mississippian of northern Arizona. Journal of Paleontology, 37(5):1074-1079.

——— 1969. Corals. In: McKee, E.D., and Gutschick, R. C., eds., History of the Redwall Limestone of northern Arizona. Geological Society of America Memoir 114, p. 257-344.

——— 1977. Significance of coiled protocoralla in some Mississippian horn corals. Paleontology, 20(1):47-58.

——— 1978. Coral zones and problems of Mississippian stratigraphy in the Williston Basin. Montana Geological Society, 24th Annual Conference, Williston Basin Symposium: 231-237.

——— 1983. Revision of *Lithostrotionella* (Coelenterata, Rugosa) from the Carboniferous and Permian. U.S. Geological Survey Professional Paper 1247, 52 p.

———— 1984. Syringoporid corals: Guides to the stratigraphy of upper Paleozoic rocks in the Western Interior region. U.S. Geological Survey Open-File Report, 84-80, 29 p.

Sando, W.J., and Bamber, E.W., 1979. Coral zonation of the Mississippian System of western North America. Ninth International Congress of Carboniferous Stratigraphy and Geology, Abstracts: 191.

———— 1985. Coral zonation of the Mississippian System in the Western Interior Province of western North America. U.S. Geological Survey Professional Paper 1334, 61 p.

———— 1977. The zoogeography of North American Mississippian corals. In: Second International Symposium on Corals and Fossil Coral Reefs, p. 175-184. Bureau de Recherches Geologiques et Minieres Memoire 89, Paris, France.

Schindewolf, O.H., 1927. Prinzipienfragen der biologischen Systematik. Palaeontologische Zeitschrift, 9:122-166.

Smith, M.H., 1960. Revised nomenclature for the Williston Basin. American Association of Petroleum Geologists Bulletin, 44(6):959-960.

Soshkina, E.D, 1928. Nizhnepermski (Artinskie) korally zapadnogo sklona severnogo Urala Moskovskiy. Obshchestva Ispyateley Prirody Byulleten, 6(3/4):337-393.

Sutherland, P.K., 1954. New genera of Carboniferous tetracorals from western Canada. Geological Magazine, 91(5):361-371.

Warren, P.S., 1927. Banff area, Alberta. Canada Geological Survey Memoir 153, 94 p.

Waters, D.L., and Sando, W.J., 1987. Coral zonules: New tools for petroleum exploration in the Mission Canyon Limestone and Charles Formation, Williston Basin, North Dakota. In: Peterson, J.A., ed., Williston Basin: Exploration Model for a Cratonic Petroleum Province. American Association of Petroleum Geologists Basin Evaluation Series, 1.

Waters, D.L., and Sando, W.J., this volume. Depositional cycles in the Mission Canyon Limestone and Charles Formation, Williston Basin, North Dakota. Fifth International Williston Basin Symposium.

White, C.A., 1883. Contributions to invertebrate paleontology no. 8, fossils from the Carboniferous rocks of the Interior States. U.S. Geological and Geographical Survey of the Territories (Hayden), Twelfth Annual Report, pt. 1:155-171.

Winchell, A., 1865. Descriptions of some new species of fossils from the Marshall Group of Michigan, and its supposed equivalent in other states; with notes on some fossils of the same age previously described. Philadelphia Academy of Natural Sciences Proceedings for 1865:109-133.

WAULSORTIAN-TYPE MOUNDS IN THE MISSISSIPPIAN OF THE WILLISTON BASIN: NEW INTERPRETATION FROM OLD CORES

R. D. SEREDA[1] AND D. M. KENT[2]

[1] *Dept. of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan*

[2] *Dept. of Geology, University of Regina, Regina, Saskatchewan.*

ABSTRACT

There has been some speculation on the existence of Waulsortian-type mounds in the Mississippian of the Williston Basin but, to date, little evidence has been found to make any positive identification. Location and recognition of Waulsortian-type mounds in the subsurface can be based on the geometry and composition of outcropping mounds of Mississippian to Permian ages in various parts of the Rocky Mountain region, as well as on their paleogeographic and paleotectonic settings.

Waulsortian-type mounds in outcrop are found in slope or toe-of-slope positions, as individual mounds (150 m across by 100 m high) or as mound complexes (1500 m across by 50 m high), and containing lime mudstone and skeletal remains. The Mississippian mounds are flanked by dipping beds of crinoidal grainstones and packstones. Sites of growth of the mounds appear to have been paleobathymetric positive elements on unstable crustal blocks.

Mounds in the Mississippian of the Williston Basin should be expected on positive elements created by repeated basement block paleotectonic or syn-depositional salt solution, the most likely localities being in the vicinity of the NACP conductor zone or proximal to the Nelson River gravity anomaly.

Two cores from the Souris Valley beds of extreme southeastern Saskatchewan contain lithologies that can be interpreted as representing mound or associated strata. One core contains unstratified lime mudstones with crinoidal debris in a geological setting in which surrounding cored wells reveal thinly bedded typical slope lithologies. The second core consists of steeply dipping crinoidal grainstones and packstones. Neither core features well developed reservoir rock, but Waulsortian-type mounds yield oil elsewhere. The reservoir potential of mounds in the Williston Basin depends on porosity enhancement by either dolomitization or exhumation of primary porosity by solution of pore-filling cements.

INTRODUCTION

Lower Carboniferous strata of western Europe and North America are characterized in places by unique carbonate buildups known as "Waulsortian mounds". Well documented descriptions exist of outcrop sections of the mounds in the Sacramento Mountains of New Mexico (Lane and Ormiston, 1982), the Big Snowy Mountains (Cotter, 1965; Smith, 1977, 1982), the Bridger Range of Montana (Stone, 1972) and Ellesmere and Axel Heiberg Islands in the Arctic (Davies, 1987). In addition to those described in outcrop, Waulsortian-type mounds have been identified in the subsurface in several localities in North America. These include mounds that contain hydrocarbons in Tennessee and Kentucky (MacQuown and Perkins, 1982), the Hardeman Basin, Texas (Ahr and Ross, 1982), and the Seal area of north-central Alberta (Morgan and Jackson, 1970; Edwards, 1986). All of these mound structures vary not only in time and space, but also in character from the type "Waulsortian" of Belgium (Lees, 1964, 1982, 1985). However, despite the differences, several primary characteristics are common to all mound structures of the Lower Carboniferous. These characteristics include a lime mudstone core, flanking grainstone or encrinite beds; associated deeper water limestone and shales, and a depositional setting on carbonate ramps (Fig. 1).

Various authors have speculated on the presence of Waulsortian-type mounds in the subsurface of the Williston Basin. McCabe (1959) noted "a few feet of very porous, extremely fossiliferous reefoid material" in the basal Lodgepole of southwestern Manitoba. Bjorlie and Anderson (1978) postulated the presence of Waulsortian-type mounds to explain the anomalous distribution of the Carrington shale facies in western North Dakota. More recently, Kent (1979, 1984) inferred their presence on the basis of the stratigraphic and sedimentological similarities between the Souris Valley beds of southeastern Saskatchewan and the mound-bearing Lodgepole Formation of Montana.

This paper presents evidence for what the authors consider to be the first documented record of Waulsortian-type mounds in the subsurface of the Williston Basin. It summarizes the preliminary results of a larger study of the Lower Mississippian Souris Valley beds, southeastern Saskatchewan, which is currently in progress (Fig. 2).

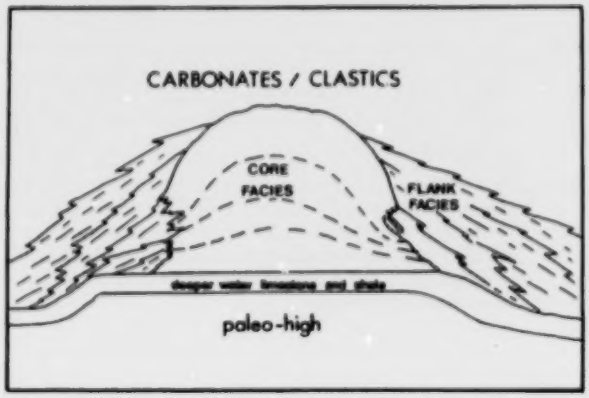


Fig. 1 Sketch model of a Waulsortian-type mound showing the relationship between the mound facies and off-mound facies. The model is based on the Muleshoe bioherm in New Mexico (Lane and Ormiston, 1982). Mounds range in height from 10 to 100 metres and are up to 1 km in diameter.

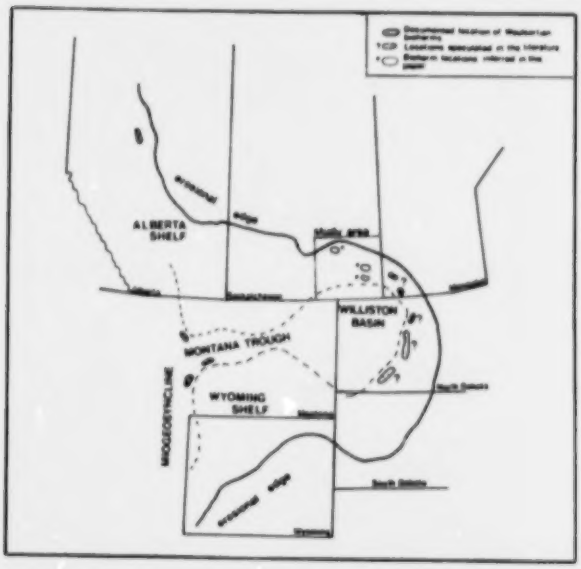


Fig. 2 Map showing known and inferred locations of Waulsortian-type mounds in the Early Mississippian of the Williston Basin.

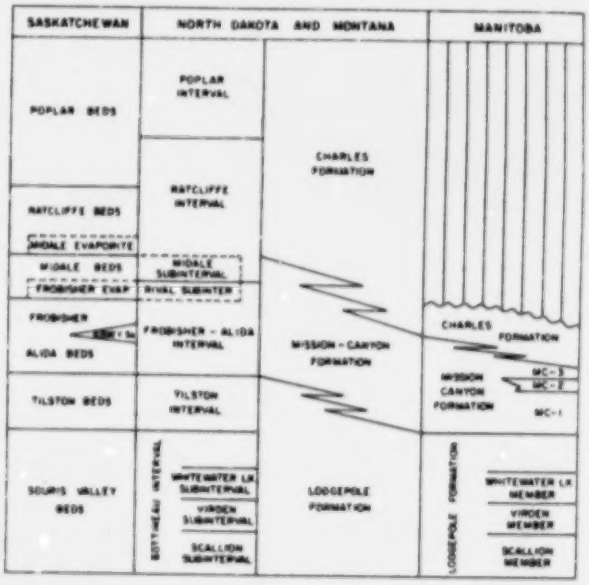


Fig. 3 Commonly accepted nomenclature for the Mississippian of the Williston Basin.

GEOLOGICAL SETTING

The Mississippian succession in southeastern Saskatchewan is thought to represent a prograding shelf-to-basin sequence (Kent, 1978, 1984). The succession is separated into seven marker-defined units (Fig. 3). Each marker is synchronous but the boundaries that separate the facies constituting the shelf-to-basin succession are diachronous. The facies include: peritidal, inner shelf, outer shelf, slope and basin. Each of the marker-defined units is truncated by the sub-Mesozoic unconformity in such a way that the peritidal, inner shelf and outer shelf rocks of the oldest units have been removed by erosion, leaving only slope and basin rocks preserved. Therefore, the vertical sequence towards the centre of the basin is more representative of the lateral facies relationships. The nomenclature applied to each marker-defined unit is illustrated in Figure 3, and the rocks of specific interest to this study are the Souris Valley beds.

The Souris Valley beds of southeastern Saskatchewan are the lowest unit of the carbonates of the Madison Group. They are considered to be equivalent to the Lodgepole Formation of Manitoba, North Dakota and Montana, and to the Banff Formation of Alberta. The Souris Valley beds were originally described by Fuller (1956), with additional information published by Edie (1958), Fuzesy (1960), and more recently by Kent (1979, 1984). In the study area, the Souris Valley sequence is composed of two broad lithofacies: a thinly bedded, lime-packstone and mudstone, and an argillaceous lime mudstone and shale.

The packstone-mudstone lithofacies represents resedimented carbonate clasts of either grain-flow or turbidite origin (Fig. 4). These are composed of coarse-grained, graded beds of crinoidal carbonates. The flow units range in thickness from 5 cm to 50 cm and rest on a scoured, burrowed base, overlain by centimetre-size rip-up clasts, grading into a fining-upward sequence of crinoidal debris. The bedding is horizontal to slightly inclined in the amount of a few degrees. The units are cyclic, and when compared to their siliciclastic analog probably represent the A-B-E portion of the classical Bouma sequence.

The lime mudstone-shale lithofacies represents carbonates that most likely were deposited in a deeper water setting. They contain varying amounts of glauconitic, pyritiferous, and bituminous particles, with minor amounts of small fossiliferous fragments (Fig. 5). In places, this fossil component becomes abundant and the rock takes on a wackestone texture. Churned and mottled textures predominate in this zone, but horizontal and cross laminations are recognized also. Kent (1979) described these rocks as having been deposited in anaerobic conditions in a deeper water setting, under "starved" conditions.

In general, the transition from packstone-mudstone to mudstone-shale appears to represent a basinward progradation in sedimentation (Edie, 1958) similar to that in the Lodgepole Formation of the central Montana trough (Smith, 1977, 1982). It bears a striking resemblance to certain features of the slope-to-basin transition on the Burlington Shelf of the midwestern United States (King, 1986) and the Redwall-Escabrosa Shelf of the southwestern United States (Gutschick and Sandberg, 1983). Waulsortian-type mounds are found in the slope-to-basin transition in these three depositional provinces.

"WAULSORTIAN-TYPE FACIES" OF THE WILLISTON BASIN AND CONTIGUOUS AREAS

OUTCROPPING MOUNDS

A brief discussion of the characteristics of the Waulsortian-type mounds of the Big Snowy Mountains of Montana is in order to develop an analogy with limited subsurface information from southeastern Saskatchewan which is thought to represent Waulsortian-type lithologies. Cotter (1965) first presented a detailed account of the mound complexes of the Big Snowy Mountains, considering them to be made up of two or more individual mounds. The typical complex is about 1500 m across at the base and ranges from 46 m to 56 m in height; it rests on a burrowed mottled, glauconitic, skeletal limestone (wackestone, packstone, and grainstone), that represents the basal Lodgepole (Kent, 1974, 1984). The mounds are enclosed

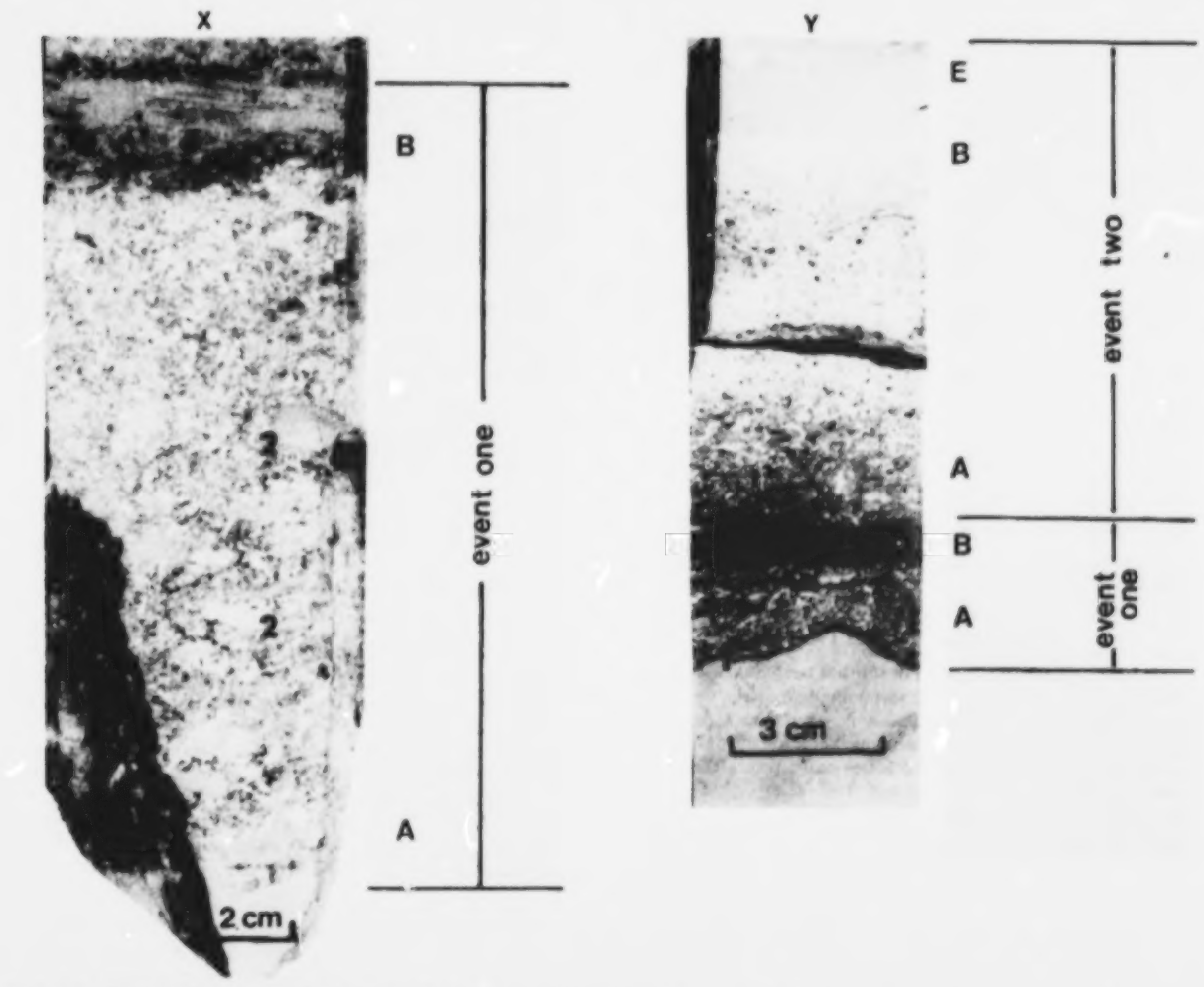


Fig. 4 Souris Valley crinoidal packstone of the shelf-slope setting. The depositional cycles are characteristic of crinoidal turbidites and consist of a scoured base (1), rip-up clasts (2), fining upward into planar laminations (3). Depositional events may be high energy as in X (Voyager Co-Enerco Mair, 4-6-9-31W1M 990.1 m), or moderate energy as in Y (Francana et al Langbank, 2-28-12-2W2M 1067.5 m) and range in thickness from 2 to 50 cm. When compared to a classic analog, the events display the A-B-E portions of a Bouma cycle.

by a dark, rhythmically bedded, argillaceous lime mudstone and more argillaceous limestone and calcareous mudrock. Fossils are rare and commonly unbroken or unabraded. In addition to crinoids, bryozoans, brachiopods and corals, ichnofossils such as *Nereites* have been identified.

The cores of the mounds consist of varying proportions of lime mudstone and skeletal debris of mound-inhabiting organisms. The former makes up about sixty per cent of the volume of the mounds, the latter, twenty-five per cent. The fossils are mostly crinoids and fenestrate bryozoans, but include brachiopods, corals, ostracods, cephalopods, trilobites, echinoids, and foraminifers. The remaining fifteen per cent is calcite cement infilling stromatactis and other voids. The mounds are compositionally layered, each layer being defined by variations of lime mudstone, fossils and cement.

According to Smith (1928), the mound-flanking beds in the Big Snowy Mountains are poorly exposed but, where visible, consist of crinoidal wackestones and packstones. The crinoid columnals are commonly articulated, and are generally larger and more abundant than in the core facies.

SUBSURFACE MOUNDS

Examination of Souris Valley cores from Suncor et al North Antler 12-08-9-30W1M, Tenneco et al Fleming 04-11-13-30W1M and Socony et al Peepeekeesis 13-11-22-11W2M, reveals lithologies similar to those associated with Waulsortian-type mound-core and mound-flanking beds.

MOUND-CORE FACIES

The lithology in the Suncor et al North Antler well is dissimilar to that of surrounding wells from the same stratigraphic interval, but strongly resembles the mound-core facies observed in outcrops of the Muleshoe bioherm, New Mexico, and in Swimming Woman Canyon, Montana. It is a lime mud with varying proportions of large skeletal fragments (Fig. 6) of, predominantly, crinoid ossicles and fenestrate bryozoans with, subordinately, brachiopods, ostracods, and corals (?). The crinoid ossicles are both articulate and disarticulate, and vary in size from 5 mm to 3 cm. The fenestrate bryozoans are more fragmented than the crinoidal debris and range in size from 1 mm to 1 cm.

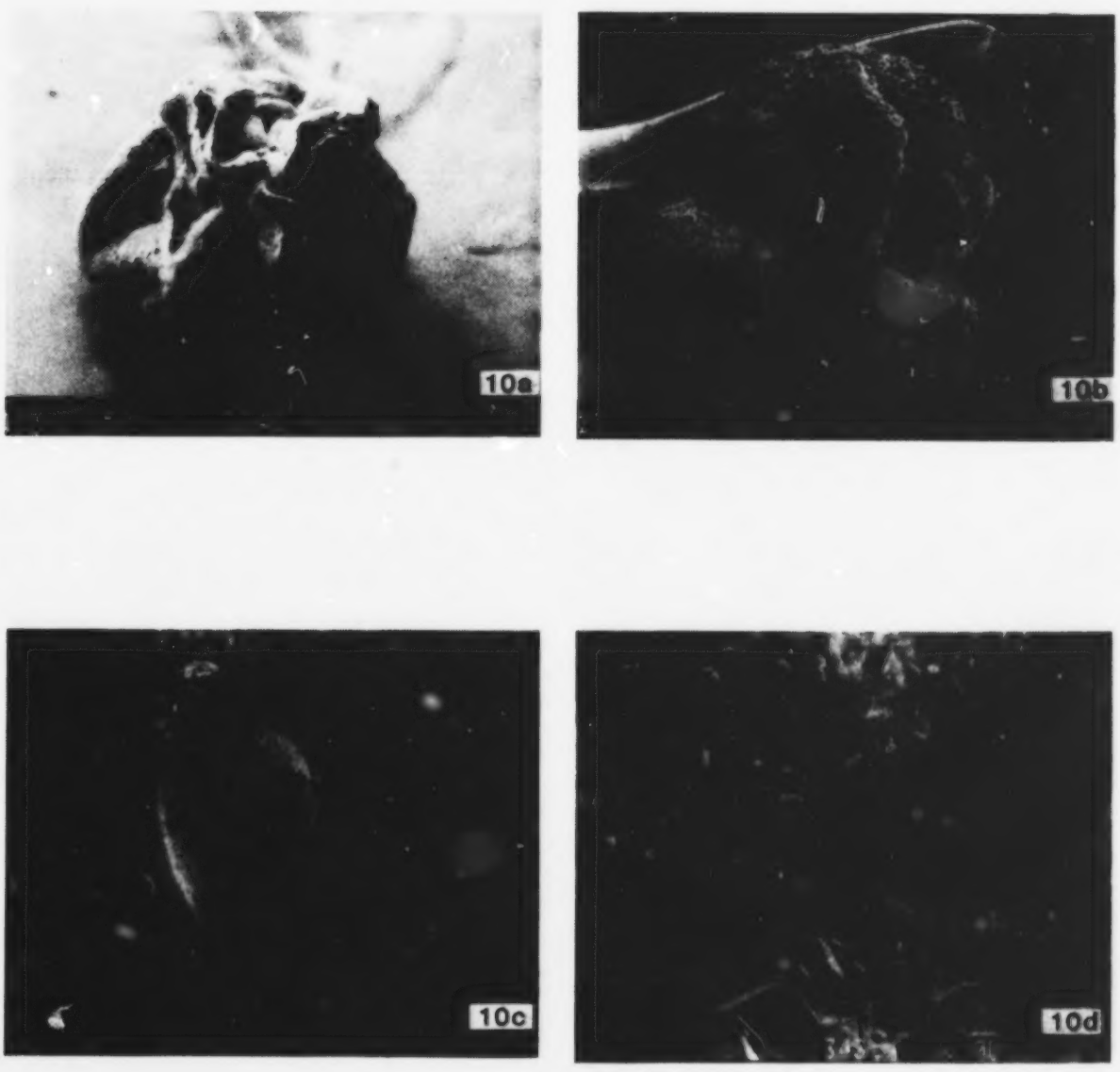
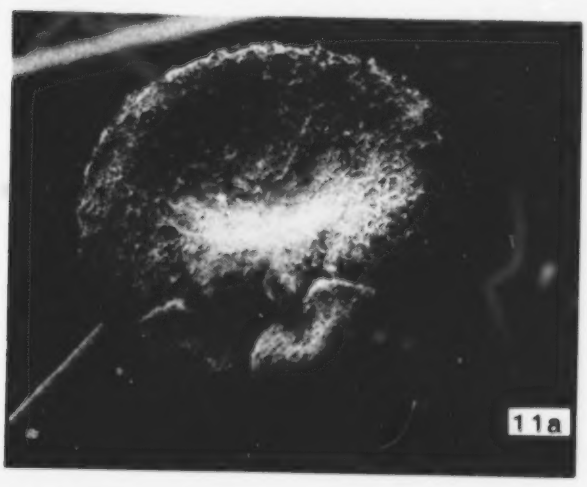
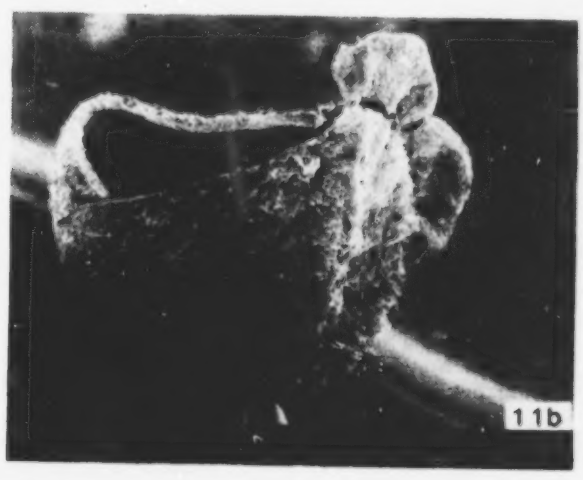


Fig. 10 Megaspores (Type 3). a) and c) from 4182 ft depth. b) from 4162 ft depth. Notice the lack of capilli or spinae. c) megaspore in dolostone matrix, arrow points to location of 10d. Scale bars in microns.

Fig. 5 Souris Valley bituminous lime mudstones and shales of the basin setting. B. A. Mobil et al Erickson, 16-30-9-30W1M, 1002.20 m

Fig. 6 Suncor et al North Antler 12-8-9-30W1M. X (912.75 to 913.25 m) and Y (916.00 to 916.50 m). The depositional fabric is indicative of a Waulsortian-type mound, core facies. Note the large crinoid ossicles floating in a lime mud matrix (arrows). The depositional fabric is present in the entire core interval and, on the gamma ray log, correlates to a structure approximately 45 m high.





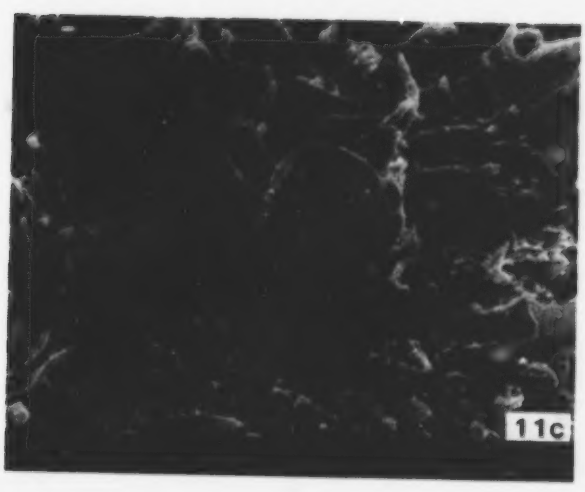


Fig. 11 Megaspores (Type 4) recovered from 4181-4182 ft depth. Very similar to Type 3, but covered with hair-like capilli. 11c is a close-up of capilli on 11b. Note partially dissolved dolomite. Scale bars in microns.

Fig. 12 Megaspore (Type 5). Possibly a portion of a tetrahedral tetrad. Recovered from 4183 ft. depth. Arrow points to rhombic impressions formed during compaction with dolomite.

Thin sections taken from the top and bottom of the cored interval reveal radiaxial fibrous calcite cement, similar to that in the mounds of the Big Snowy Mountains, suggesting early submarine cementation in a phreatic zone. As illustrated in Figure 7, the cement is prominent on bryozoan and crinoid fragments.

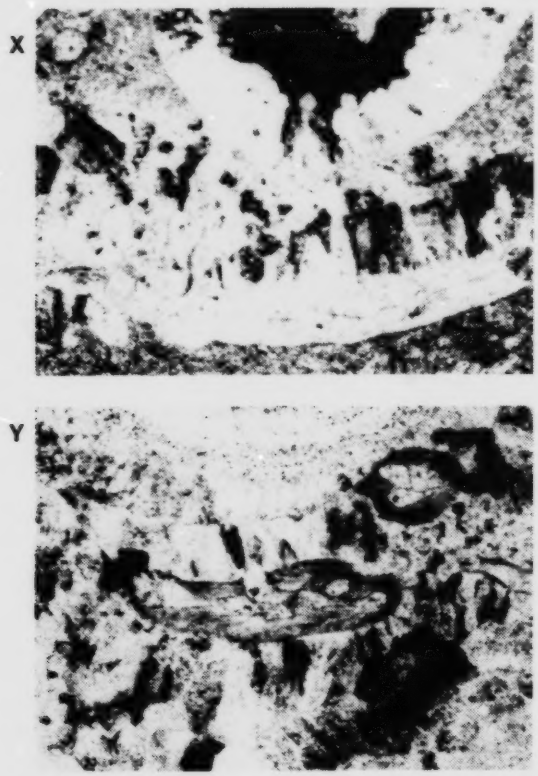


Fig. 7 Photomicrograph of mound-core facies, X (921.80 m) and Y (921.36m) as displayed in Figure 6. Note the dominance of radiaxial calcite rimming brachiopod and crinoid particles.

The percentage ratio of mud to skeletal fragments varies from 25:75 to 85:15 resulting in packstone to wackestone textures. Beds range from 5 cm to 30 cm thick and are characterized by fossil-rich and fossil-poor layers. Geophysical log measurements indicate that this mound structure is approximately 45 m high.

MOUND-FLANK FACIES

Waulsortian-type mound-flank facies is indicated in the Tenneco et al Fleming, and Socony et al Peepeekeesis wells. Their cores display steeply dipping beds of interbedded mudstones and grainstones (Fig. 8). Beds vary from 5 cm to 15 cm in thickness and dip at angles up to 40°. The grainstone layers are composed predominantly of crinoid ossicles and fenestrate bryozoans. The crinoid ossicles are angular and range in size from 1 mm to 3 cm. Bryozoan fragments are more abraded than the crinoid remains and lie parallel to bedding. In both wells, the depositional fabric displayed in Figure 8 is present in the basal 10 m of the core but some original texture has been destroyed by dolomitization.

Fig. 8 Tenneco et al Fleming 4-11-13-30W1M, 724.00 to 724.40 m (X), and Socony et al Peepeekeesis 13-11-22-11W2M, 710.40 to 710.85 m (Y). Depositional fabric indicative of a Waulsortian-type mound, flanking facies. Note the steeply dipping interbeds of lime mud and crinoidal grainstones. In Y, the depositional fabric has been obscured by dolomitization.

The writers are aware of the inherent danger of basing any form of interpretation on three widely spaced boreholes. However, the Suncor et al North Antler and Tenneco et al Fleming wells are in the same general area, and may be on mound trends similar to those in the Fort Payne Formation of Tennessee (MacQuown and Perkins, 1982) or in the Pekisko Formation of the Seal area of north-central Alberta (Edwards, 1986). Seismic interpretation is an important tool for recog-

nition of the mounds of the Seal area and might be useful in southeastern Saskatchewan also. However, unlike the Seal area, where mounds are enclosed by mudrock, velocity contrast between mound and slope carbonates in the Souris Valley beds may be insufficient for discrimination. In the absence of more seismic information, it is speculated that the Suncor et al North Antler well is located on a structural anomaly responsible for localization of a mound or mound cluster.

LOCALIZATION OF MOUND GROWTH

All previous accounts of Mississippian Waulsortian-type mounds indicate that mound growth was localized on paleobathymetric highs. However, opinions vary as to mound genesis and include three basic arguments:

1) a mechanical accumulation of sediment (Wilson, 1975),
2) a structural high on the sea floor (Miller and Grayson, 1982 and Smith, 1982), or
3) a combination of both structure and sedimentation (George and Ahr, 1986).

Certainly mounds in outcrop are located in regions that have undergone pronounced tectonism, suggesting their localization on positive features possibly related to uplifted crustal blocks.

In the subsurface of southeast Saskatchewan, two mechanisms are thought to have created the features that influenced sedimentation at various times during the Phanerozoic. The first is associated with basement tectonics such as block faulting, the second with the multistage solution of Devonian salt (Smith and Pullen, 1967), which also may have been initiated by basement lineaments (Kent, 1973, 1974).

The tectonic configuration of the sub-Phanerozoic Williston Basin is speculative. Indorf and Norwood (1983), Mueller and Klipping (1978), and Sharp (1978) have postulated faulted basement block movements for the Williston Basin in Montana. The existence of such features in southeastern Saskatchewan is not yet proven, but if present, they may have become the focus of mound growth in the manner proposed for mounds in Montana (Smith, 1982) and northern England (Miller and Grayson, 1982) (Fig. 9). However, the postulated mounds of southeastern Saskatchewan are located in the vicinity of the Nelson River gravity trend (Fig. 10), which is thought to be related to an Early Proterozoic plate boundary and collision zone. McCabe (1967) and Kent (1984) suggested that this trend exerted control on some oolitic shoals in the Ordovician Red River Formation and the delineation of the margin of the Middle Devonian Winnipegosis shelf. The inferred genetic relationship of the trend with the basement makes the trend a possible focus for block faulting or multistage salt solution, either of which could have exercised some control on the siting of Waulsortian-type mounds.

Stratigraphic stacking has been demonstrated as a means of localizing mounds, as illustrated by the Pennsylvanian Virgilian algal mounds of the Sacramento Mountains, New Mexico. Similarily, Mississippian Waulsortian-type mounds in southeastern Saskatchewan may have been constrained to positions above older buildups, particularly where dissolution of Prairie Evaporite salts has occurred above and around Middle Devonian Winnipegosis "reefs". Dissolution of the salt would result in draping of younger strata over the "reefs" (see Norris et al, 1982). If it occurred syndepositionally (Early Mississippian), it would have formed the requisite paleobathymetric highs for siting Waulsortian-type mounds (Fig. 11).

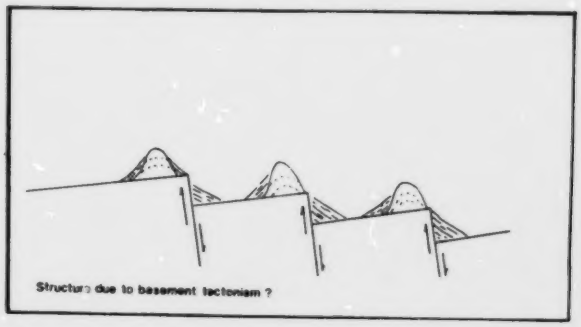


Fig. 9 Mechanism to isolate Waulsortian-type mound growth as postulated by Smith (1982) for Montana and Miller and Grayson (1982) for northern England.

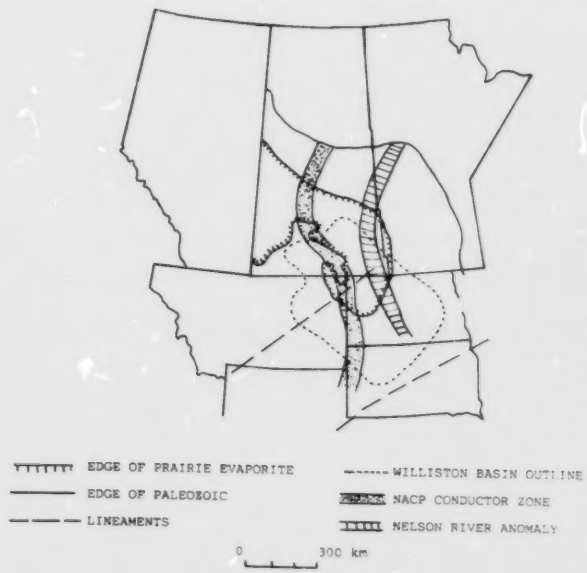


Fig. 10 Structural elements present in the Williston Basin.

ECONOMIC CONSIDERATIONS

In the Fort Payne Formation of Tennessee, over six million barrels of oil have been produced since 1924 from several mounds and mound trends (average thickness 25 m). Primary production is taken from the core facies, which is an interbedded wackestone and packstone composed predominantly of bryozoans and ostracod fragments (MacQuown and Perkins, 1982). Reservoir porosity is mainly in the grain-supported layers of the mound-core facies. Porosity is primarily interparticle and vuggy, created by dissolution of early cements and further enhanced by fracturing.

The Quanah Field of the Hardeman Basin in Texas is a fractured and extensively dolomitized Waulsortian-type mound (Ahr and Ross, 1982). The field is pumped by one well and has yielded 388 barrels per day from the core facies (Ahr and Ross, 1982).

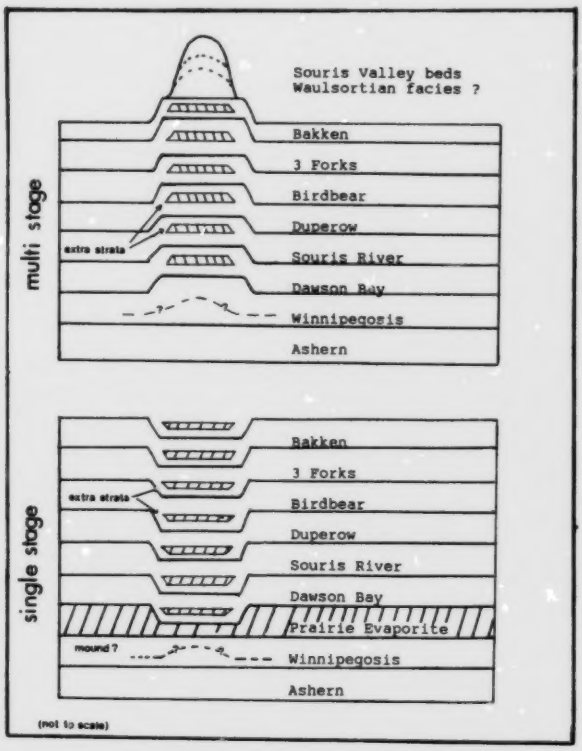


Fig. 11 Multi stage salt-solution mechanism creating isolated structure which may be the focus of Waulsortian-type mound growth in southeast Saskatchewan.

The most recent discovery of oil in a Waulsortian-type mound is in the Seal area of north-central Alberta. The Pembina et al Seal 07-06-82-12W5M well, drilled in 1983, encountered 32 m of net pay in the core facies. The reserves consist of approximately 8.03 x 10^5 m^3 of 11.7 degrees API oil-in-place. The porosity is mainly incompletely cemented, vuggy intra- and inter-particle, as well as biomoldic and channel. Permeability is enhanced to some extent by vertical fractures (Edwards, 1986).

Many outcrop mounds are extensively cemented and so are poor models of potential reservoir porosity. However, the mounds of the Big Snowy Mountains of Montana have an irregular, 0 to 15 m thick cap which features biomoldic and intercrystal porosity and which could have made a good reservoir given proper conditions of burial. In the Souris Valley beds of southeast Saskatchewan, none of the wells believed to have penetrated Waulsortian-type mounds displays exploitable porosity. The mound-flank wells, Socony et al Peepeekeesis 13-11-22-11W2M and Tenneco et al Fleming 04-11-13-30W1M, are dry and abandoned. The mound-core well, Suncor et al North Antler, produced 62 barrels of oil per day for 13 days but then declined until shut in.

SUMMARY

Waulsortian-type mounds commonly occur in Lower Mississippian rocks, in a slope-to-basin depositional setting, in many parts of the United States. Since a similar setting exists in the Lower Mississippian of the Williston Basin, similar mounds might be expected there as well.

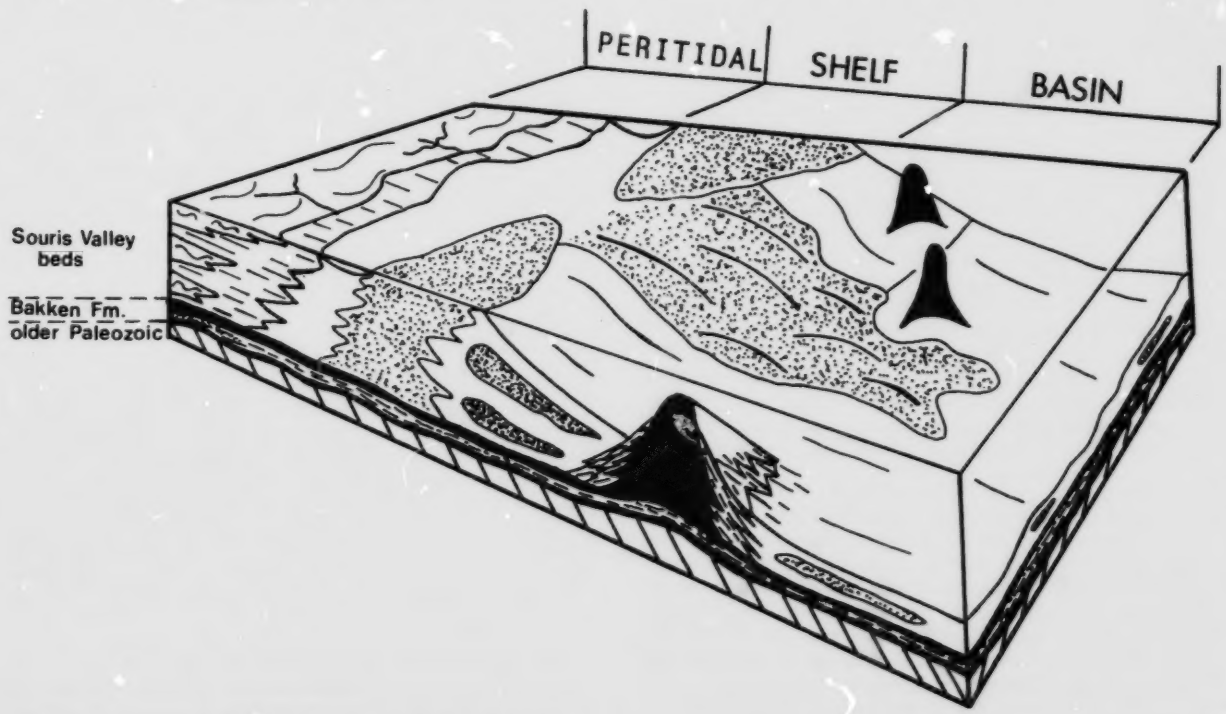


Fig. 12 Carbonate ramp model for southeast Saskatchewan during the Early Mississippian. Peritidal and shelf environments truncated by the sub-Mesozoic unconformity. Modifed from Kent, 1984 and Read, 1985.

Preliminary evidence of three Waulsortian-type mounds in the lower slope-to-basin facies of the Souris Valley beds has been found in southeastern Saskatchewan. One of the wells reveals a mound-core facies of thickly bedded crinoidal wackestones. The other two contain steeply dipping, thinly bedded grainstones representative of a mound-flank facies. The fairly wide distribution of the wells make interpretation tenuous, but two of the wells lie along a basement trend and thus could be part of a mound cluster controlled by the structure.

Short-term production was obtained from the mound-core well, but the other two wells showed no exploitable reservoir porosity. However, in Tennessee, Kentucky and Texas, Waulsortian-type mounds yield oil and consequently indicate a future for similar buildups as exploration targets in the Williston Basin.

ACKNOWLEDGEMENTS

This paper is derived from research for a M. Sc. thesis currently in preparation at the University of Saskatchewan. The topic is a regional evaluation of the Lower Mississippian Souris Valley beds of southeast Saskatchewan by R. D. Sereda under the supervision of Dr. W. K. Braun of the University of Saskatchewan and Dr. D. M. Kent of the University of Regina.

REFERENCES CITED

Ahr, W. M., and Ross, S. L., 1982, Chappel (Mississippian) biohermal reservoirs in the Hardeman Basin, Texas: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 221-225.

Bjorlie, P. E., and Anderson, S.B., 1978, Stratigraphy and depositional setting of the Carrington shale facies (Mississippian) of the Williston Basin: Montana Geological Society, 1978, Williston Basin Symposium, p. 165-176.

Cotter, E. J., 1965, Waulsortian-type carbonate banks in the Mississippian Lodgepole Formation of central Montana: Journal of Geology, v. 73, p. 881-888.

Davies, G. R., 1987, Upper Carboniferous Waulsortian-type bryozoan reefs, Canadian Arctic Archipelago (Abstract): Canadian Society of Petroleum Geologists, Program, Reef Research Symposium, p. 25.

Edie, R.W., 1958, Mississippian sedimentation and oilfields of southeastern Saskatchewan: American Association of Petroleum Geologists Bulletin, v. 42, pp. 94-126.

Edwards, D., 1986, Lower Carboniferous carbonate mounds in the Seal area: Krishelle Enterprises Ltd., Calgary, Alberta, unpublished report, 16p.

Fuller, J. G. C. M., 1956, Mississippian rocks and oilfields in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report No. 19, 72p.

Fuzesy, L. M., 1960, Correlations and subcrop of the Mississippian strata in southeastern and south-central Saskatchewan: Saskatchewan Energy and Mines Report No. 51, 63p.

George, G. G., and Ahr, W. M., 1986, The effects of paleotopography and substrate lithology on the origin of Waulsortian reefs: south-central Sacramento Mountains, New Mexico: Gulf Coast Association of Geological Societies Transactions, v. 36, p. 129-139.

Gutschick, R. C., and Sandberg, C. A., 1983, Mississippian continental margins of the conterminous United States. In: Stanley, D. J., and Moore, G. T., eds., The Shelfbreak: Critical Interface on Continental Margins: Society of Economic Paleontologists and Mineralogists Spec. Publ. No. 33, p. 79-96.

Indorf, C. P., and Norwood, E. E., 1983, Development of structure and porosity at the Medicine Lake Field in northeast Montana, Williston Basin. (Abstract): American Association of Petroleum Geologists Bulletin, v. 67, p. 1343-1344.

Kent, D. M., 1973, Paleozoic hydrocarbon reservoirs in Saskatchewan and their relationship to basement lineaments: Journal of Canadian Petroleum Technology, v. 12, p. 20-24.

Kent, D. M., 1974, Relationship between hydrocarbon accumulations and basement structural elements in the northern Williston Basin. In: Parslow, G. R., ed., Fuels: a Geological Appraisal: Saskatchewan Geological Society Spec. Publ. No. 2, p. 63-80.

Kent, D. M., 1979, Shelf margin to deep water depositional environments in the Mississippian System of the northern Williston Basin (Abstract): Montana Geological Society, 1978 Williston Basin Symposium, p. 205-206.

Kent, D. M., 1979, Mississippian reservoirs in Williston Basin: Compte Rende, Ninth International Congress on Carboniferous Stratigraphy and Geology, Urbana, Illinois, May, 1979.

Kent, D. M., 1984, Depositional setting of Mississippian strata in southeastern Saskatchewan: a conceptual model for hydrocarbon accumulation. In: Lorsong, J. A., and Wilson, M. A., eds., Oil and Gas in Saskatchewan: Saskatchewan Geological Society Spec. Publ. No. 7, p. 19-30.

Kent, D. M., 1984, Carbonates and associated rocks of the Williston Basin: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Short Course Notes, 135 p.

King, D. T., 1986, Waulsortian-type buildups and resedimented (carbonate-turbidite) facies, early Mississippian Burlington shelf, central Missouri: Journal of Sedimentary Petrology, v. 56, p. 471-479.

Lane, H. R., and Ormiston, A. R., 1982, Waulsortian facies, Sacramento Mountains, New Mexico: Guide for an International Seminar, March 2-6, 1982. In: Bolton, K., Lane, H. R., and Lemone, D. V., eds., Symposium on the Environmental Setting and Distribution of the Waulsortian Facies: El Paso Geological Society and University of Texas at El Paso, p. 115-182.

Lees, A., 1964, The structure and origin of the Waulsortian (Lower Carboniferous) "reefs" of west-central Eire: Philosophical Transactions of the Royal Society of London, B. 247, p. 483-531.

Lees, A., 1982, The paleoenvironmental setting and distribution of the Waulsortian facies of Belgium and southern Britain. In: Bolton, K., Lane, H. R., and Lemone D. V., eds., Symposium on the Environmental Setting and Distribution of the Waulsortian Facies: El Paso Geological Society and University of Texas at El Paso, p. 1-16.

Lees, A., 1985, Facies variation in Waulsortian buildups II: Mid-Dinantian buildups from Europe and North America. Geology Journal, v. 20, p. 159-180.

Lees, A., Hallet, V., and Hibo, D,, 1985, Facies variation in Waulsortian buildups I: A model from Belgium. Geology Journal, v. 20, p. 133-158.

MacQuown, W. C., and Perkins, J. H., 1982, Stratigraphy and petrology of petroleum-producing Waulsortian-type carbonate mounds in the Fort Payne Formation (Lower Mississippian) of north-central Tennessee: American Association of Petroleum Geologists Bulletin, v. 66, p. 1055-1075.

McCabe, H. R., 1959, Mississippian stratigraphy of Manitoba: Manitoba Mines Branch, Publ. 58-1, 99 p.

McCabe, H. R., 1967, Tectonic framework of the Paleozoic formations in Manitoba: Transactions of the Canadian Institute of Mining and Metallurgy, v. 70, p. 180-189.

Miller, J., and Grayson, R. F., 1982, The regional context of Waulsortian facies in northern England. In: Bolton, K., Lane, H. R., and Lemone, D. V., eds., Symposium on the Environmental Setting and Distribution of the Waulsortian Facies, El Paso Geological Society and University of Texas at El Paso, p. 17-33.

Mueller, C. A., and Klipping, R. S., 1979, Geology and geophysics of Sioux Pass Field, Richland County, Montana. In: Montana Geological Society, 24th Conference, 1978 Williston Basin Symposium, p. 345-354.

Norris, A. W., Uyeno, T. T., and McCabe, H. R., 1982, Devonian rocks of the Lake Winnipegosis-Lake Manitoba outcrop belt: Geological Survey of Canada Memoir 392, Manitoba Department of Energy and Mines Publ. 771, 280p.

Read, J. F., 1985, Carbonate platform facies models: American Association of Petroleum Geologists Bulletin, v. 69, p. 1-21.

Sharp, R. W., 1978, Geology of the Vaux Field area, Richland County, Montana. In: Montana Geological Society 24th Conference, 1978 Williston Basin Symposium, p. 283-292.

Smith, D. G., and Pullen, J. R., 1967. Hummingbird structure of southeast Saskatchewan: Bulletin of Canadian Petroleum Geology, v. 15, No. 4, p. 468-482.

Smith, D. L., 1977, Transition from deep to shallow-water carbonates, Paine Member, Lodgepole Formation, central Montana. In: Enos. P., and Cook, H. E., eds., Deeper-water Carbonate Environments: Society of Economic Paleontologists and Mineralogists Spec. Publ. No. 25, p. 187-201.

Smith, D L., 1982, Waulsortian bioherms in the Paine Member of the Lodgepole Limestone (Kinderhookian) of Montana, U.S.A. In: Bolton, K., Lane, H. R., and Lemone, D. V., eds., Symposium on the Environmental Setting and Distribution of the Waulsortian Facies: El Paso Geological Society and University of Texas at El Paso, p. 51-64.

Stone, R. A., 1972, Waulsortian-type bioherms (reefs) of Mississippian age, central Bridger Range, Montana. In: Montana Geological Society Guidebook p. 37-55.

Wilson, J. L., 1985, Carbonate Facies in Geological History: Springer-Verlag, New York, 471 p.

ENVIRONMENTAL SIGNIFICANCE OF A MEGASPORE FLORA FROM THE MISSION CANYON FORMATION (MISSISSIPPIAN), BOTTINEAU COUNTY, NORTH DAKOTA

MARK R. LUTHER[1], EDWARD N. STEADMAN[2] AND LEN V. HILLS[3]

[1]*Department of Geology and Geological Engineering, University of North Dakota, Grand Forks;*
[2]*Energy Research Center, University of North Dakota, Grand Forks;*
[3]*Department of Geology and Geophysics, The University of Calgary.*

ABSTRACT

Megaspores and unidentified plant fragments have been recovered from two thin (0.5 m - 1.5 m) zones within carbonates of the Frobisher-Alida interval of the Mississippian Mission Canyon Formation. This flora was found during a study of the Wiley Field, southwestern Bottineau County, North Dakota. At least five new forms of megaspores were found, and are believed to represent previously undescribed genera and species of arborescent lycopods. Arborescent lycopods are typically associated with fresh-water environments. The remarkable preservation, low diversity, and apparent areally restricted concentration of megaspores indicate growth at or near the place of deposition. This may provide evidence for local subaerial exposure and fresh-water lens development. Preserved organic fragments were deposited in nearby topographic lows. Organic plant and scolecodont material was preserved in an anoxic shallow water setting probably caused by saline brines. These brines dolomitized the sediments in which the organic material was preserved before significant compaction had occurred.

INTRODUCTION

Although plant fragments have been described from Mississippian rocks of the Williston Basin, these reported findings are rare. Webster (1982) and Thrasher (1985) found plant fragments in the Bakken Formation (Devonian and Mississippian) in North Dakota. Thrasher (1985) described blade-like "leaves", woody plant fragments, and possible plant stems. He considered the blade-like "leaves" to mark the base of the Mississippian in the Williston Basin.

Earlier, Fuller (1956) noted plant remains from Mississippian rocks in the Saskatchewan portion of the Williston Basin. He found nearly all the plant fragments in the Charles Formation, and a few "carbonized plant remains" in the Hastings-Frobisher Beds (upper Mission Canyon Formation). Fuller (1956) stated that some of these fragments resemble "equisetalian plants". To our knowledge, the above-mentioned descriptions of unidentified, poorly preserved plant fragments are the only documented occurrences of plants from the Mississippian of the Williston Basin.

Recently, however, extremely well-preserved plant remains have been recovered from Mississippian carbonates of the Mission Canyon Formation in the northeastern portion of the Williston Basin. Luther (in preparation), in a wireline log and core study of the Wiley Field (Township 161N. and Ranges 81W. and 82W. in Bottineau County, North Dakota, Fig. 1) found plant fragments while describing core from a well just south of the field boundary (Fig. 2). This well, NDGS# 3343, California Oil Company's O. C. Haugen #1, NE1/4NW1/4 Sec. 26, T. 161 N., R. 82 W., contained well preserved organic plant and animal fragments in two separate dolostone units just beneath the K2 (Kisbey) marker (LeFever and Anderson, 1986., Fig. 2).

METHODS

Core was slabbed and examined with a reflected light microscope and hand lens. Plant remains were first noted

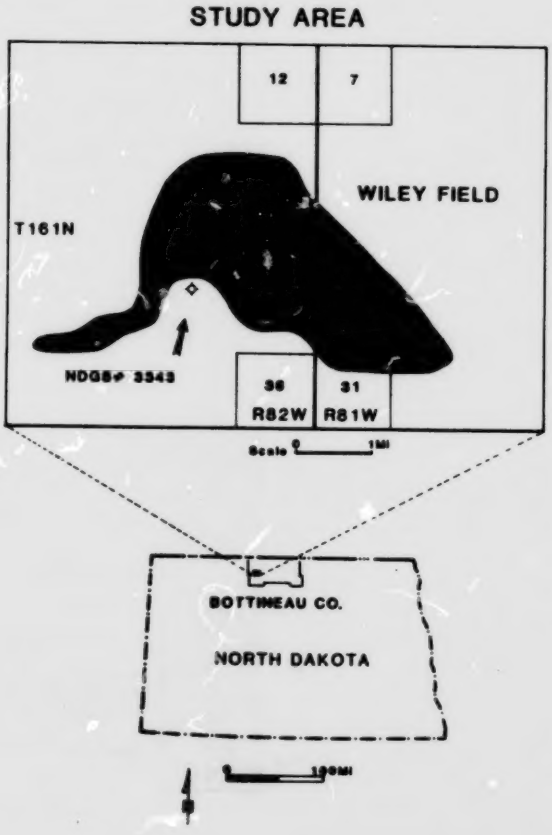


Fig. 1 Location of NDGS# 3343 relative to the Wiley Field.

visually on bedding planes of core sections. This led to examination of both slabbed and exterior core surfaces with a microscope. Several organic fragments were found by this process including several blade-like "leaves", possible plant stems, and numerous scolecodonts (Fig. 3), including at least one complete jaw assemblage. A few isolated, well-preserved fragments, later determined to be plant megaspores, were also found.

A small portion of the predominantly dolostone core from the interval in which organic fragments were found was then dissolved in dilute acetic acid (10%) to recover any organic or phosphatic floral and faunal elements. The resulting insoluble residue was washed through a 3-phi sieve to collect the larger fragments. This was dried, and then examined and sorted with a microscope. An SEM/ Microprobe was used to analyze and photograph high-resolution images of selected organic fragments.

STRATIGRAPHY OF THE FROBISHER-ALIDA INTERVAL

The Wiley Field produces from carbonates of the Mission Canyon Formation in which hydrocarbons are trapped by updip laterally equivalent, and overlying evaporites of the Charles Formation. Since these carbonates are located beneath the K2 marker (Kisbey sandstone) and above the K3 marker, they are considered to be part of the Glenburn beds (LeFever and Anderson, 1986) (Fig 4). The Glenburn bed is approximately 50 ft. (15 m) thick within the study area.

Cores of the Glenburn bed to the south (basinward) of the Wiley Field contain increasing numbers and varieties of fossils. Well #3343, from which the plant fragments and scolecodonts were taken, occurs in a transitional area between predominantly coated-grain lithotypes (shoreward) and fossiliferous lithotypes (basinward).

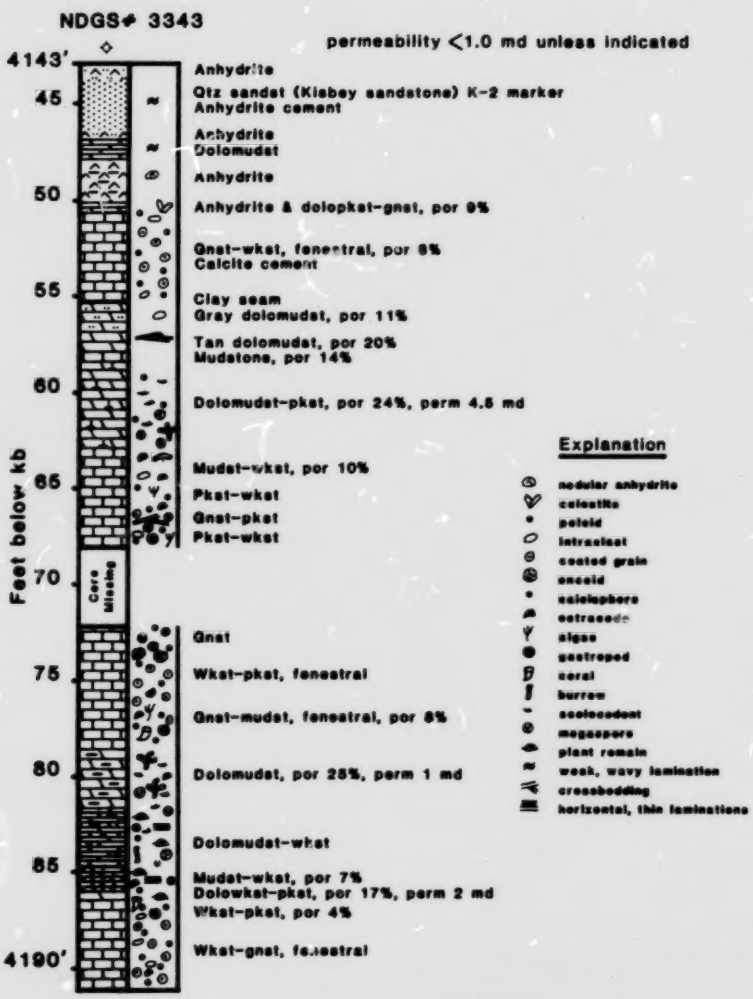


Fig. 2 Lithologic column for described core from NDGS# 3343 illustrating lithology, grain types and packing, sedimentary structures, porosities and permeabilities (millidarcy). Plant material and scolecodonts are found only in dolostones or dolomitic limestones. Porosities and permeabilities are greater in zones containing megaspores and scolecodonts.

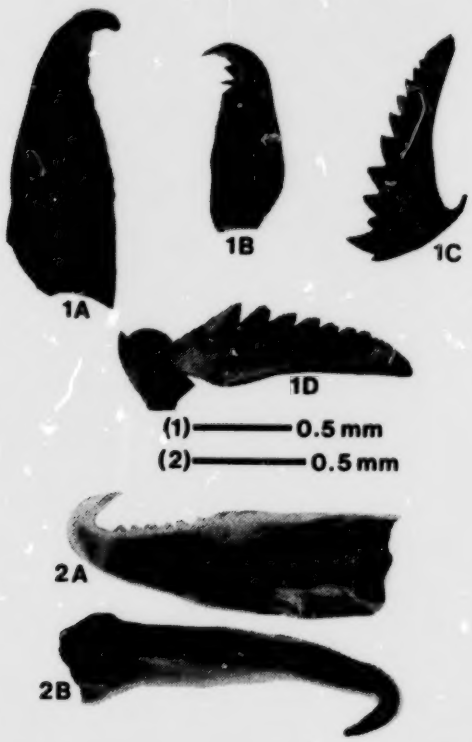


Fig. 3 Scolecodonts recovered from core taken at a depth of 4180 ft. from well #3343. Note hollow jaw (3-2A) which is typical for scolecodonts, but not for conodonts. Color ranges from black to brown-black.

Deposition of the Glenburn bed is here interpreted to have taken place during a time of equilibrium between relative sea level and sedimentation rates. This is indicated by the lack of lateral migration of predominantly inorganic allochems (basinward) and evaporites (shoreward) within the study area. This equilibrium ended at approximately the time of deposition of the K2 marker, when evaporite deposition abruptly extended basinward over the underlying carbonates.

Both isopach maps and core descriptions (Luther, in preparation) indicate that well #3343 was located in a NE-SW-trending topographic low extending to the shoreward evaporite-producing zones. This low is adjacent to coated-grain lithotypes that formed low relief (3 m) topographic highs in basinward portions of the Wiley Field. It is on these topographic highs that megaspore-producing plants are thought to have become established.

DESCRIPTIONS

Preliminary examination of the megaspores suggests that there are five distinct types. The following general descriptions and illustrations of the megaspores are intended to alert other investigators to these microfossils. No taxonomic determinations will be given here except to suggest that these types represent the megaspores of arborescent lycopods and represent both new genera and species. Further taxonomic treatment is forthcoming in future publications.

Type one (Figs. 8a through 8d) appears to be a trilete spore, and is roughly triangular. Ornamentation consists of prominent spinae (Figs. 8c and 8d). The illustrated specimen is about 1.4 mm long in the long axis.

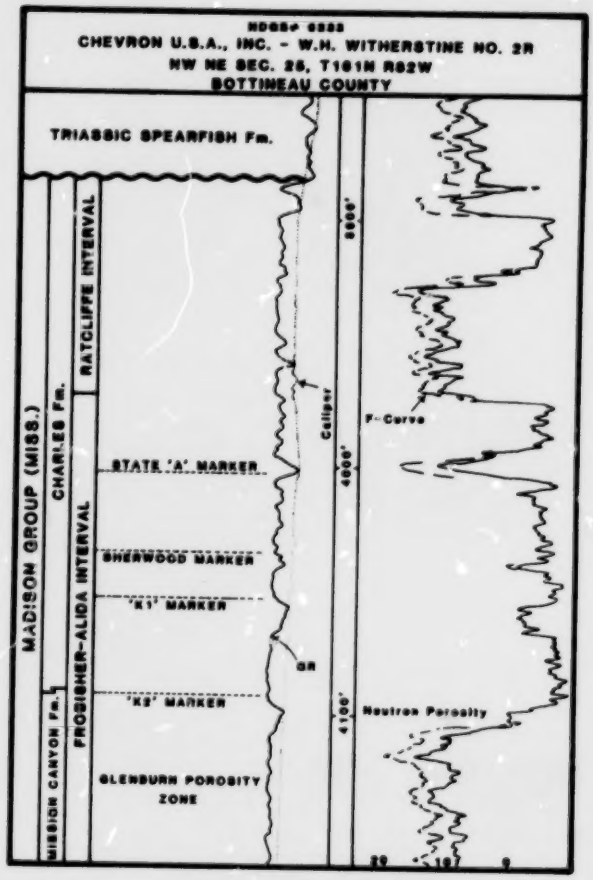


Fig. 4 A wireline log from a typical producing well in the Wiley Field, illustrating formations and informal intervals and markers. Nonporous anhydrites of the Charles Formation overlie porous carbonates of the Glenburn bed (Mission Canyon Fm.).

Type two (Figs. 9a through 9d) also appears to be a trilete spore, and is roughly triangular. Ornamentation is echinate to subechinate; spinae are less elongate and more rounded than those found in type one. The illustrated specimen is about 1.5 mm long in the long axis.

Type three (Figs. 10a through 10d) is spherical, and has prominent proximal architecture in the form of massa (or gula?). The exine surface appears smooth. The diameters are approximately 1.5 mm and 0.9 mm in the illustrated specimens.

Type four (Figs. 11a through 11c) is spherical and has prominent massa or gula on the proximal surface. This form is basically similar in overall morphology to type three except for the surface ornamentation. The surface of type four is covered with hair-like capilli (Fig. 11c) that are winding but not branched. The illustrated specimens are approximately 1.5 mm and 1.2 mm in diameter.

Type five (Fig. 12) appears to be a portion of a tetrahedral tetrad, and is roughly spherical. The broken area is facing upward in the illustrated specimen. Several specimens of this type were encountered. The illustrated specimen is approximately 0.55 mm in diameter.

Fig. 5 Plant remain located on a bedding plane, and typical of those found in well #3343.

Fig. 6 Horizontally-laminated, dolomitic limestone to calcitic dolostone in which most plant fragments other than megaspores were found. Scolecodonts were not found in this type of deposit.

DEPOSITIONAL MODEL

Several factors indicate that plant fragments found in core from well #3343 originated near the place of deposition. These factors include: 1) the presence of previously undescribed forms of megaspores, representing new genera and species; 2) the relative abundance of megaspores with low diversity that were found (indicating a local, isolated origin), rather than the small number of very diverse megaspores that would be expected if transported from a continental source; 3) the apparent areal restriction of the organic fragments as indicated by the absence of preserved plant fragments in described core from 28 other wells generally located updip (shoreward) of #3343; 4) the excellent preservation and lack of abrasion observed in the organic fragments; 5) the presence of burrows and scolecodont assemblages in the upper portions of the megaspore-containing zone, thus precluding transport of all organics to the site of deposition; and 6) the presence of topographic highs composed of coated grains, on which plants may have become established adjacent to the place of deposition.

The coated-grain highs are the most likely area in which megaspore-producing plants might have become established. At least two different environmental settings may be envisioned. One setting involves coated-grain highs that were isolated, subaerially-exposed, positive features due to a small sea-level drop. A fresh-water lens could form in the exposed sediments, most likely underlain by the hypersaline marine brines that also filled the adjacent low. Plants, such as arborescent lycopods, generally thought to grow in fresh water, may have become established on these isolated highs and contributed plant material, including megaspores, to the immediate vicinity including the adjacent low.

In the other setting, arborescent lycopods became established in shallow marine waters, much like do modern mangroves. Once again the coated-grain highs would be the most likely areas in which this took place. The relative lack of current-produced sedimentary structures in the coated-grain highs suggests a stable substrate on which the arborescent lycopods could become established. As previously stated, arborescent lycopods are thought to have grown in fresh water environments. However, Schopf and Askin (1980) have suggested that the Triassic arborescent lycopod *Pleuromeia* may have formed mangrove-type associations.

PRESERVATION

To inhibit the oxidation and decomposition of the organic plant fragments found in well #3343, deposition in an anoxic or reducing environment is required. This environment may be caused by several conditions, including: very low-energy waters containing abundant organic material, rapid burial, or as Kinsman et al (1974) noted, saline brines capable of evaporate precipitation. Evidence found in the study area supports only the last (increased salinities) of these conditions.

Kinsman et al (1974) found that increasing the concentration of marine water brines led to gradually lower concentrations of dissolved oxygen. At the point at which halite-precipitation

Fig. 7 Burrowed dolomudstone from which abundant scolecodonts were recovered.

could occur these brines were considered anoxic under all but the most turbulent conditions. Increased water temperatures reduced the amount of dissolved oxygen even more, to the point at which gypsum-precipitation brines would be nearly anoxic.

Anoxic conditions, due to the presence of concentrated brines in the topographic low in which the plant fragments are interpreted to have been deposited, can be supported in either of the previously discussed depositional settings. Dense saline brines would tend to concentrate in lows during a sea level drop (first setting), or may flow basinward through the NE-SW-trending low (location of well #3343) as an undercurrent from the shoreward, evaporite-precipitating, sublittoral flats (second setting).

Further evidence supporting this interpretation of organic preservation by anoxic saline brines is that organic fragments in well #3343 were found in thin dolostone sections not present in cores from adjacent coated-grain highs. Near-surface formation of this dolomite is indicated by the lack of compaction of both scolecodonts and megaspores and the presence of rhombic impressions on the exterior surfaces of some of these organic fragments (Fig. 12). This suggests that the dolomite formed before substantial compaction took place.

Dolomite formation by gypsum-precipitating brines is well documented. Many authors, including Sears and Lucia (1980), have called upon gypsum-precipitating brines to cause dolomitization of sediments. Brines with a high Mg/Ca ratio produced by evaporation of seawater and the precipitation of gypsum in shallow, shoreward flats could easily dolomitize sediments and preserve organic fragments.

CONCLUSIONS

Several conclusions and areas of possible future study are drawn from this research, including:

1) Identifiable organic remains were found including scolecodonts and previously undescribed forms of megaspores that originated at or near the place of deposition in Mississippian Mission Canyon carbonates of the Williston Basin.
2) A plant type (arborescent lycopod) generally associated with fresh-water environments was found in marine carbonates and may indicate subaerial exposure of coated-grain highs and formation of a fresh-water lens within these highs.
3) Nearly anoxic, shallow-water conditions were present in the vicinity of well #3343 during the deposition of plant material and burrowing of sediments by scolecodont-bearing polychaete worms. These conditions prevented the decomposition of organic fragments.
4) Saline brines that produced the anoxic conditions during the deposition of organic fragments also dolomitized the sediments in which they were found before significant compaction had begun. This indicates early, near surface dolomitization of sediments, or primary dolomite formation.

In addition, porosities and permeabilities are greater in zones in which saline brines preserved organics and dolomitized sediments than they are in underlying or overlying limestones. Porosity trends formed by similar brine movements may provide migration routes or reservoirs for hydrocarbons, and could be a target for exploration in the future. The possibility that land plants may have locally contributed to hydrocarbon accumulations should also be explored.

ACKNOWLEDGEMENTS

Core and logs were supplied by the North Dakota Geological Survey, whose personnel have provided much assistance. Partial funding of the study that led to this paper was provided by Tenneco Oil Exploration and Production. Dr. Robert Stevenson of the University of North Dakota Natural Materials Analytical Laboratory is thanked for his assistance with SEM/Microprobe analyses. Dr. Francis M. Hueber of the Smithsonian Institution provided initial identification of the megaspores as well as helpful comments. Dr. Howard J. Fischer (University of North Dakota) contributed valuable observations and discussions, although the responsibility for interpretations rests with us. The manuscript benefited from critical comments by Dr. Alan M. Cvancara and Jean Hoff (University of North Dakota).

REFERENCES CITED

Fuller, J. G. C. M., 1956, Mississippian rocks and oilfields in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources, Petroleum and Natural Gas Branch Report No. 19, 72 p.

Fig. 8 A trilete megaspore (Type 1) recovered from 4182 ft depth. a) looking at cut surface and hollow interior. b) straight edge on the right is the result of a saw cut during core slabbing. c) and d) note well preserved spinae.

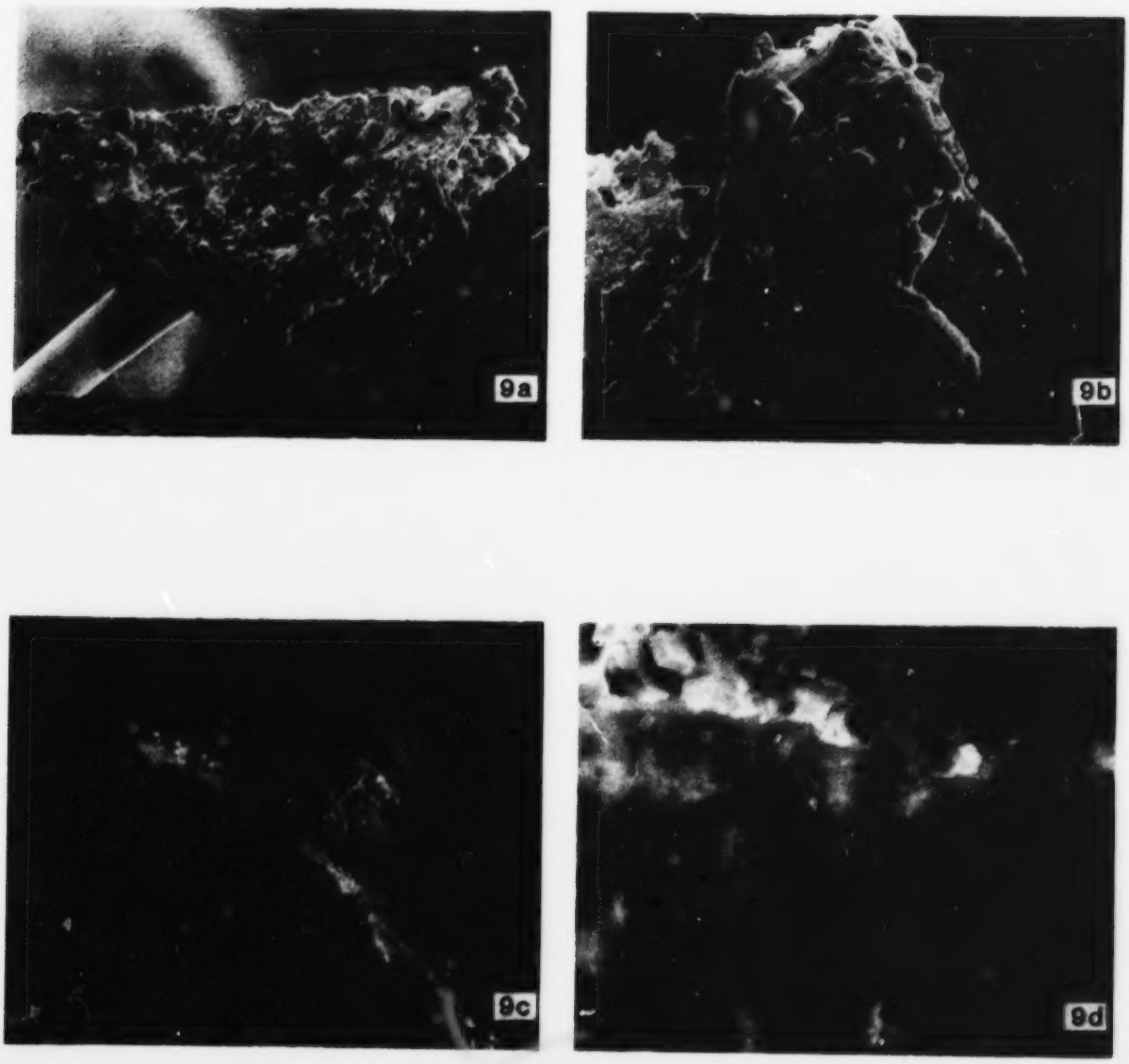


Fig. 9 A trilete megaspore (Type 2) recovered from 4183 ft depth. Megaspore has short, blunt spinae. a) arrow points to location of 9b. b) note dolomite which wasn't totally removed by acid. c) Megaspore within dolostone. Arrow points to location of 9d. d) close-up of exine (spore wall). Scale bars in microns.

Kinsman, D. J. J., Boardman, M., and Brocsik, M., 1974, An experimental determination of the solubility of oxygen in marine brines, In: Coogan, A. H. (ed.), Fourth symposium on salt: Northern Ohio Geological Society, Cleveland, OH., v. 1, p. 325-327.

LeFever, J.A., and Anderson, S. B., 1986, Structure and stratigraphy of the Frobisher-Alida and Ratcliffe intervals, Mississippian Madison Group, north-central North Dakota: North Dakota Geological Survey, R.I. No. 84, 17 p.

Luther, M.R., Depositional environment and diagenesis of the Mississippian Frobisher-Alida interval, Wiley Field, northcentral North Dakota: unpublished M.Sc. thesis, University of North Dakota, Grand Forks, in preparation.

Schopf, J. M., and Askin, R. A., 1980, Permian and Triassic floral biostratigraphic zones of southern land masses, In: Dilcher, D. L. et al, (eds.), Biostratigraphy of fossil plants; successional and paleocological analyses: Stroudsburg, PA., U.S.A., Dowden, Hutchinson and Ross, p. 119-152.

Sears, S. O., and Lucia, F. J., 1980, Dolomitization of northern Michigan Niagara reefs by brine refluxion and freshwater/seawater mixing, In: Zenger, D. H., Dunham, J.B., and Ehington, R. L. (eds.), Concepts and models of dolomitization: Society of Economic Paleontologists and Mineralogists Special Publication No. 28, p. 215-235.

Thrasher, L.C., 1985, Macrofossils and biostratigraphy of the Bakken Formation (Devonian and Mississippian) in western North Dakota: unpublished M.Sc thesis, University of North Dakota, Grand Forks, 292 p.

Webster, R. L., 1982, Analysis of petroleum source rocks of the Bakken Formation (Devonian-Mississippian) in North Dakota: unpublished M.Sc. thesis, University of North Dakota, Grand Forks, 150 p.

CYCLICITY IN THE MISSION CANYON AND LOWER CHARLES FORMATIONS OF THE CENTRAL WILLISTON BASIN

JEAN L. HOFF

Department of Geology and Geological Engineering
University of North Dakota
Grand Forks, North Dakota 58202

ABSTRACT

Statistical analysis was performed on 414 metres (1357 ft) of core from the Mission Canyon and Charles Formations of the central Williston Basin of North Dakota. Carbonate and sulfate lithologies from the Ratcliffe, Frobisher-Alida, and Tilston intervals were sampled and examined for the presence of cyclicity. Binary (presence-absence) data were collected for 50 lithologic components. Similarity measures were calculated using the phi association coefficient. Unweighted pair-group mean clustering was performed on the similarity matrices. The significance of clusters was tested using chi-square related 99 per cent and 95 per cent confidence levels. Clusters significant at the 99 per cent level have distinct lithologic identities and are interpreted as lithofacies. Lithofacies were used as the mutually exclusive states required by numerical analysis of cyclicity. Iterative, simultaneous use of embedded Markov chain and mutual substitutability analyses was followed by examination of relative entropy patterns.

Markov property was determined to be present in each of the three wells studied. Two or more pairs of states were found to be mutually substitutable in each well. In all wells, patterns of Markov dependencies were resolved into two cycles. In NDGS 793, one type of cycle is formed by oolitic packstones and grainstones, the other by more restricted marine facies which include dolomitic mudstone, bedded sulfate, and intraclastic and microfossiliferous wackestones. In NDGS 1262, one group of 5 cyclic facies are echinoderm wackestones, packstones, and grainstones; the other cycle type is composed of restricted marine facies including oolitic facies, dolomitic mudstone, sulfates, and ostracod and calcisphere-bearing wackestones. The differences between the two types of cyclicity identified in NDGS 7207 are less easily recognized than in the other wells. One set of transitions contains relatively more restricted marine facies but both include the brachiopod-echinoderm facies.

Entropy patterns for all wells suggest that cyclicity in the central Williston Basin is symmetrical. No conclusions can be drawn from the depth distribution of lithofacies in NDGS 7207. The stratigraphic distribution of lithofacies forming cycles in wells 793 and 1262 shows a clear and abrupt change from the more restricted marine facies in the upper portion of the cored interval, to the echinoderm-bearing carbonates or oolitic facies. This indicates abrupt rather than gradual introduction of more evaporative facies and control of upper and lower cyclicity by separately operating depositional mechanisms.

INTRODUCTION

Workers in the Williston Basin have repeatedly reported the presence of cyclicity within the lithologic succession of the Mission Canyon and Charles Formations (Mississippian). Cyclicity has been identified on several geographic and stratigraphic scales—ranging from cycles of local extent and only a few metres thick (Elliott, 1982; Lindsay and Roth, 1982), to cycles of regional extent with thicknesses greater than 100 metres (Harris and others, 1966; Waters, 1984). Cyclicity in the Madison Group of the Williston Basin has been attributed to many mechanisms, including large and small-scale repetitive regression, local migration of shoal and off-shoal facies, and repeated restrictive events.

To date, studies reporting cyclicity in the Mission Canyon and Charles Formations have been qualitative in nature. In addition to doubts that have been raised generally about human ability to spot cyclicity and non-cyclicity (Zeller, 1964), there are problems with the methodology and assumptions of some of this previous work. Such problems include: 1) biases during the examination for cyclicity due to expectations arising from genetic interpretation of lithologies; 2) use of depositional models based on modern carbonate analogies which may not be valid in ancient intracratonic settings such as the Williston Basin; and 3) generalizations from field-scale studies to regional problems.

This paper presents initial results of a statistically-based investigation of cyclicity in the Mission Canyon and lowermost Charles Formations of the Williston Basin in North Dakota. To avoid the preconceptions and assumptions of previous workers, statistical techniques were used to group lithologies as well as for numerical analysis and description of cyclicity. In this paper results from cores in the central portions of the Williston Basin will be discussed.

METHODS

Cores totalling 414 metres (1357 feet) in length were examined from three wells in the central portion of the Williston Basin (Fig. 1). Wells were primarily chosen for maximum continuous stratigraphic coverage of the Mission Canyon Formation. A secondary criterion was inclusion of as much of the lower Charles Formation as possible. Portions of the Ratcliffe, Frobisher-Alida, and Tilston intervals are included in the cores discussed in this paper (Fig. 2).

Rather than at random or fixed intervals, samples were taken from each visually distinguishable unit. To ensure maximum consistency during the definition of these units, all core was slabbed and cleaned before examination. Any questionable units were sampled and multiple samples were taken from thick units. All samples were slabbed and etched. Grains and cements were selectively stained to help distinguish calcite, dolomite, and sulfates.

Slabs were examined microscopically and 50 components (Table 1) were counted on a presence-absence basis. Binary data are used to increase the number of samples that can be examined. Lithologic components were chosen to reflect depositional rather than diagenetic processes. Most components are grain types or sedimentary fabric characteristics. Some components that reflect early diagenetic processes were included because they can be correlated to depositional features. For example, microstylolites and broken bioclasts

Fig. 1 Location map of three wells used in this study within central Williston Basin. Base map after Worsley and Fuzesy (1978).

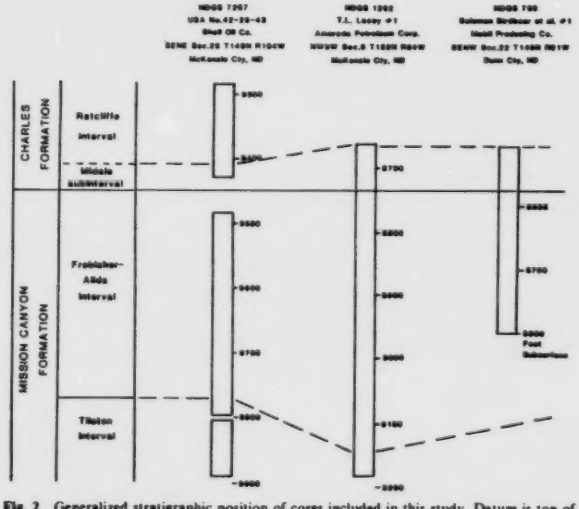


Fig. 2 Generalized stratigraphic position of cores included in this study. Datum is top of Frobisher-Alida interval.

may both result from early mechanical compaction (Shinn and Robbin, 1983) and thus may indicate muddier depositional textures than are presently preserved.

Similarity measures were calculated between samples from the binary data using the phi association coefficient as suggested by Hohn (1976) in his paper examining performance and theoretical bases of various binary coefficients. The phi coefficient is related algebraically to the chi-square statistic and thus is preferable to other binary coefficients because the statistical significance of associations can be directly tested.

Table 1. Lithologic components identified.

INORGANIC GRAINS	ORGANIC GRAINS
ooid	unidentified microfossil
pisoid	unidentified macrofossil
composite coated grain	
pellet/peloid	calcisphere
intraclast	ostracod
irregular vuggy intraclast	nodular codiacean alga
lithoclast	gastropod
FABRIC CHARACTERISTICS	foraminiferid
	brachiopod
whole bioclast	echinoderm
broken bioclast	bryozoan
abraded bioclast	solitary coral
	colonial coral
fenestrae or sheet cracks	bivalve
crust or hardground	trilobite
lamination	**COMPOSITIONAL FEATURES**
cross lamination or bedding	
sorting	micrite in matrix
graded bedding	grain support
mudcracks	silicification
boring	dolomitic
burrows	carbonate cement
bioturbation	sulfate cement
pattern mottling	argillaceous
stylolite	pyrite
microstylolite	
replacive sulfate	
lath-shaped sulfate	
nodular sulfate	
mosaic or nodular-mosaic sulfate	
massive sulfate	

Unweighted pair-group mean clustering (Sneath and Sokal, 1973, p. 230) was performed on the similarity matrices. The phi coefficient value determined from the chi-square value for the 99 per cent confidence level and the number of variables is used as the cut-off value when identifying statistically significant clusters. Clusters that join at similarity levels below this value are considered distinct and statistically significant. Clusters that join between the 99 per cent and 95 per cent significance levels of calculated phi coefficient values are treated as significant subsets of the larger clusters. Isolated samples that join clusters at similarity levels below the 99 per cent confidence level are not considered members of significant cluster and are therefore ignored during Markov analysis. Examination of the variables most frequently present and absent in each cluster yields the lithologic identity of the clusters.

Significant clusters with distinct lithologic identities are considered to be lithofacies. The lithofacies identified in each of three wells of this study are described in Table 2. These lithofacies meet the criteria as mutually exclusive states required in, and are therefore used for, numerical analysis of cyclicity.

Cyclicity analysis consists of iterative, simultaneous use of first-order embedded Markov chain and mutual substitutability analyses. During this procedure the nature of the overall pattern of cyclicity was checked using the entropy analysis of Hattori (1976). The methodology of Powers and Easterling (1982) was followed during embedded Markov chain analysis. This is distinguished by the use of a model of quasi-independence and the computation of Z values for use in identification of significant transitions. This procedure identifies states which follow other states more often than would be expected in a purely random sequence and hence tests for the presence of cyclicity.

Substitutability analysis identifies states that are interchangeable within a sequence. Left and right (upward and downward) substitutabilities are determined and multiplied to obtain mutual substitutability which identifies states that are likely to occur between the same preceding and succeeding states. Mutual substitutabilities were calculated and clustered

Table 2. Lithologic characteristics of significant clusters.

Well	Facies	Description
793	1	fenestral, calcisphere, pellet/peloid packstone-grainstone
	2	fenestral, compacted,ooid, pellet/peloid, intraclast, microfossil,calcisphere packstone-grainstone
	3	fenestral, mottled,ooid, pellet/peloid packstone
	4	fenestral, pisoid, composite coated grain, pellet/peloid packstone
	5	fenestral, compacted, ooid, composite coated grain, pellet/peloid packstone-grainstone
	6	sulfate-bearing, ooid, pellet/peloid packstone
	7	burrowed, bioturbated, sulfate-bearing, microfossil, wackestone-mudstone
	8	pellet/peloid, intraclast packstone-wackestone
	9	compacted, microfossil mudstone and fossiliferous, intraclast wackestone-packstone
	10	massive to nodular-mosaic sulfate
	11	dolomitic mudstone interbedded with nodular to mosaic sulfate
1262	1	compacted, microfossil, echinoderm wackestone-packstone
	2	compacted, macrofossil, echinoderm, solitary coral wackestone-packstone
	3	silicified, microfossil, macrofossil, echinoderm wackestone
	4	microfossil wackestone
	5	macrofossil, echinoderm packstone-grainstone
	6	sulfate-bearing, dolomitic mudstone
	7	fenestral, ooid, pellet/peloid, intraclast packstone-grainstone
	8	calcisphere, pellet/peloid, intraclast, ostracod mudstone-wackestone with bedded sulfate
	9	pellet/peloid, calcisphere wackestone-packstone
7207	1	compacted, macrofossil, microfossil, brachiopod, echinoderm, bryozoan packstone-wackestone
	2	compacted, macrofossil, brachiopod, echinoderm packstone-wackestone
	3	compacted, macrofossil, echinoderm, solitary coral packstone-grainstone-wackestone
	4	compacted, argillaceous, brachiopod, echinoderm wackestone
	5	pellet/peloid, microfossil, calcisphere,ostracod packstone-wackestone
	6	microfossil wackestone
	7	bioturbated, compacted, microfossil, ostracod, brachiopod, echinoderm,bryozoan packstone-wackestone
	8	pyritic, compacted, microfossil, brachiopod, echinoderm wackestone interbedded with silicified packstone
	9	pyritic, compacted, microfossil, brachiopod, echinoderm packstone-wackestone
	10	microfossil, brachiopod, echinoderm grainstone-packstone
	11	brachiopod, echinoderm, bryozoan packstone-wackestone-grainstone
	12	mottled, dolomitic mudstone with nodular to massive sulfate

according to the procedure outlined in Davis (1986). Lithofacies which cluster at a high level of substitutability are considered mutually substitutable and may be combined for further Markov analysis.

The final phase of cyclicity examination was the entropy analysis of Hattori (1976). Relative pre-entropies are derived from the upward transition matrix and plotted against relative post-entropies which are derived from the downward transition matrix. These plots may be compared to the set of possible entropy patterns for various types of successions presented by Hattori (1976, p. 482). Although not a statistical test, these comparisons indicate the probable nature of the overall pattern of cyclicity.

CYCLICITY ANALYSIS

Numerical cyclicity analysis of the Mission Canyon and lower Charles Formations in the central Williston Basin demonstrates the presence in the succession of significant Markov property. In all three units dependencies are resolved into two distinct sets of transitions — or cycle types — which are characterized by differing lithofacies assemblages in different wells. These distinct cycles show no Markovian interactions between them.

NDGS 793

Markov analysis of core from NDGS 793 (Mobil Producing Co. - Birdbear #1) yields the two sets of distinct dependencies shown in the flow chart in Figure 3A. One of the cycle types is formed by lithofacies 1 through 6 and is characterized by dominantly unidirectional, strongly significant, first-order transitions. The lithofacies are fenestral grainstones and packstones distinguished from one another by differing combinations of ooids, pisoids, pellets, composite coated grains, microfossils, and calcispheres (Table 2). Mutual substitutability analysis (Fig. 3B) indicates that lithofacies 2 and 6 are interchangeable within the cycle. The undirectional nature of the strongly significant transitions is suggestive of multi-stage discrete cycles rather than merely oscillatory behavior and could be consistent with migration of oolitic shoals and microfossiliferous, calcisphere carbonate facies.

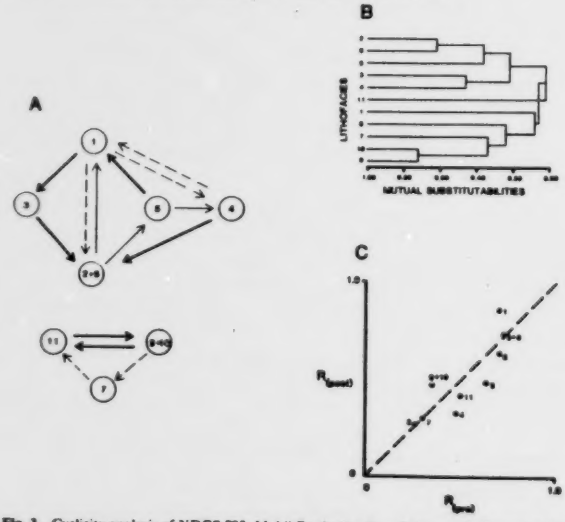


Fig. 3 Cyclicity analysis of NDGS 793, Mobil Producing Co. - Solomon Birdbear et al #1.
A) Summary flow chart of cyclicity showing Markov dependencies between lithofacies after combination of substitutable lithofacies 2 and 6, 9 and 10. Thin arrows represent significant transitions, thick arrows represent strongly significant transitions, thick arrows represent strongly significant transitions, and dashed arrows represent transitions that are slightly less than significant.
B) Dendrogram of mutual substitutabilities clustered between lithofacies.
C) Graphed relative pre-entropies (upward transitions) versus relative post-entropies (downward transitions) calculated for lithofacies of NDGS 793 after substitutability analysis.

The other distinct set of Markov dependencies is formed by lithofacies 7 through 11 (Fig. 3A). High mutual substitutabilities are shown by early clustering of lithofacies 9 and 10. Combination of states 9 and 10 prior to calculation of Markov properties shown in the lower flow chart (Fig. 3A) eliminated

transitions from lithofacies 7 and 8 due to the presence of strong transitions of lithofacies 11 with 9 and 10. Thus, the dominant cyclicity among these lithofacies is oscillation of dolomitic mudstone with interbedded sulfate (lithofacies 11, Table 2) with massive to nodular-mosaic sulfates (lithofacies 10) or intraclastic and microfossiliferous mudstone and wackestone (lithofacies 9).

The plot of relative entropies for lithofacies transitions in NDGS 793 (Fig. 3C) is characterized by scatter of points along the 45 degree line. This most closely approximates Hattori's (1976) type B plot and therefore indicates that the cyclicity present in this well is probably symmetric in nature. This would be consistent with the interpretation of the oolitic cyclicity as a product of migrating shoal facies but does not in itself eliminate other interpretations.

NDGS 1262

Identification, using Markov and substitutability analyses, of significant transitions in NDGS 1262 (Amerada Petroleum Corp. - T. L. Lacey #1) also yields two distinct and independent cycle types (Fig. 4A). Five lithofacies (1-5, Table 2) form a set of transitions between micro and macrofossiliferous, echinoderm-bearing wackestones and packstones, and echinoderm grainstones. Features which distinguish these lithofacies include: compaction, silicification, and additional faunal elements (solitary corals and bryozoans versus ostracods). These facies can be generally described as relatively open marine since they are characterized by brachiopods, echinoderms, and bryozoans—faunal elements indicating near marine salinities and oxygenated water. Mutual substitutability analysis (Fig. 4B) indicates that lithofacies 1 and 3 are substitutable, clustering at a high level by comparison to successive clustering steps. The dominant transitions after substitution are between echinoderm grainstone (lithofacies 5) and coral-echinoderm wackestone (2), and from microfossiliferous wackestone (4) to silicified echinoderm wackestone (1 + 3) to echinoderm grainstone (5). This suggests interpretation of the cyclicity as alternation between echinoderm shoals and more muddy facies.

Lithofacies 6 through 9 form a second set of transitions in core from NDGS 1262 (Fig. 4A). This cycle type contains wackestones and mudstones containing ostracods, calcispheres, intraclasts, and pellets; oolitic grainstone and packstone; dolomitic mudstone; and sulfates (Table 2). These lithologies indicate more restricted marine conditions than the other cyclicity present in this well. Lithofacies 7 and 8 show high mutual substitutabilities (Fig. 4B). Their combination reduces this cycle type to dominantly oscillation between lithofacies 9 and 7 + 8, with less frequent transitions to lithofacies 6, the sulfate-bearing dolomitic mudstone.

Entropy analysis of lithofacies in well 1262 (Fig. 4C) yields a field falling along the 45 degree line, suggesting as in NDGS 793 (Fig. 3C) the presence of symmetrical cyclicity. The relative entropy values are generally higher here than in the previous well and may indicate a higher degree of disorganization in the cyclicity of the well.

NDGS 7207

After several iterations of substitutability and Markov analyses, the pattern of Markov dependencies in NDGS 7207 (Shell Oil Co. - USA No. 42-28-43) is also resolved into two distinct sets of significant transitions (Fig. 5A). As indicated by high levels (greater than 0.60) of clustering in Figure 5B, lithofacies 1 and 9, 2 and 10, and 3 and 11 are mutually

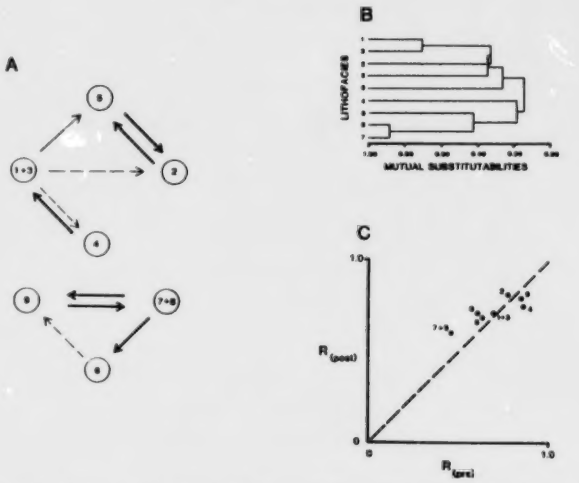


Fig. 4 Cyclicity analysis of NDGS 1262, Amerada Petroleum Corp. - T. L. Lacey #1.
A) Summary flow chart of cyclicity showing Markov dependencies between lithofacies after combination of substitutable lithofacies 1 and 3, 7 and 8. Thin arrows represent significant transitions, thick arrows represent strongly significant transitions, and dashed arrows represent transitions that are slightly less than significant.
B) Dendrogram of mutual substitutabilities clustered between lithofacies.
C) Graphed relative pre-entropies (upward transitions) versus relative post-entropies (downward transitions) calculated for lithofacies of NDGS 1262 after substitutability analysis.

substitutable. Lithologic distinctions between the two cycle types are more difficult to make than in the two previously discussed wells. The upper cycle type (Fig. 5A) contains more relatively restricted lithologies: dolomitic mudstone and bedded sulfates (lithofacies 12, Table 2); calcisphere, ostracod, and microfossil-bearing carbonates (5, 6). However, brachiopod-echinoderm facies occur in both types of cycles. In addition, the lower cycle (Fig. 3A) contains the bryozoan and coral-bearing lithologies (3, 7, 11) and silicified units (8). Thus, the upper set of transitions appears to contain more evaporative or restricted lithologies than the lower but both contain units which indicate relatively normal marine conditions.

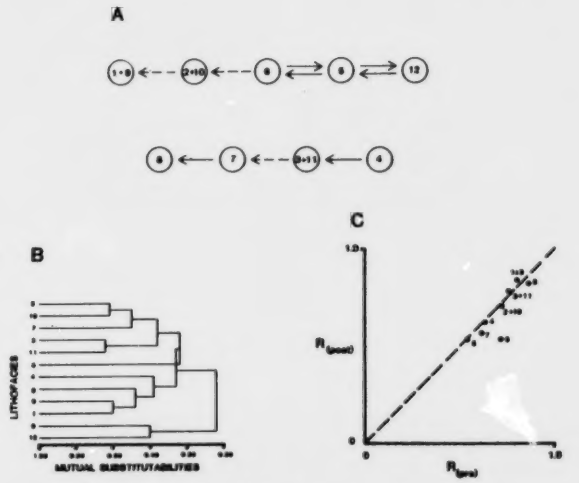


Fig. 5 Cyclicity analysis of NDGS 7207, Shell Oil Co. - USA No. 42-28-43
A) Summary flow chart of cyclicity showing Markov dependencies between lithofacies after combination of substitutable lithofacies 1 and 9, 2 and 10, 3 and 11. Solid arrows represent statistically significant transitions. Dashed arrows represent transitions that are slightly less than significant.
B) Dendrogram of mutual substitutabilities clustered between lithofacies.
C) Graphed relative pre-entropies (upward transitions) versus relative post-entrophies (downward transitions) calculated for lithofacies of NDGS 7207 after substitutability analysis.

The entropy relationships shown by the lithofacies in NDGS 7207 (Fig. 5C) are similar to those in NDGS 1262 (Fig. 4C) — the points fall along the line but have a moderately high value. This again suggests the presence of symmetric cyclicity in the sequence.

STRATIGRAPHIC DISTRIBUTION OF CYCLICITY

An abrupt change in the distribution of lithofacies is present in both NDGS 793 and NDGS 1262 (Figs. 6A, 6B). In well 793 (Fig. 6A) the upper portion of the core is dominated by the relatively restricted marine lithofacies (7-11), whereas the lower interval is dominated by lithofacies 1 through 6 which comprise the ooid-coated grain-pisoid cyclicity. There is a clear separation in the distribution of these two groups of lithofacies. The change from one to the other is abrupt, taking place over approximately 10-15 ft (3-5 m) at a depth of about 8645 to 8660 feet subsurface. This abrupt change is located in the upper portion of the Frobisher-Alida interval (Fig. 2).

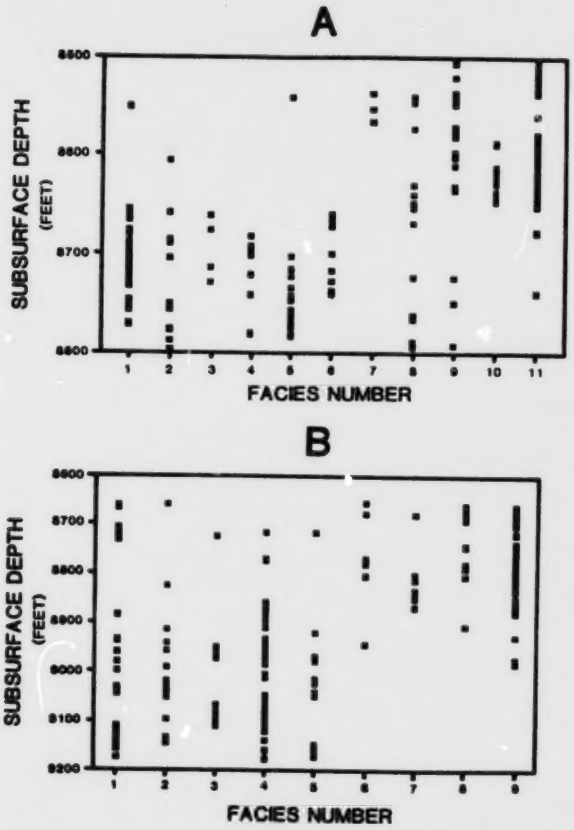


Fig. 6 Stratigraphic distribution of lithofacies in wells NDGS 793 and NDGS 1262.
A) Depth (subsurface) distribution of lithofacies 1 through 11 identified in core from NDGS 793.
B) Depth (subsurface) distribution of lithofacies 1 through 9 identified in core from NDGS 1292.

In NDGS 1262 (Fig. 6B) the change is from echinoderm-bearing lithofacies in the lower portion of the well (lithofacies 1-5) to relatively more restricted marine biota, dolomite, and sulfate-bearing lithologies of lithofacies 6 through 9. There is again clear stratigraphic separation of facies in the two types of cycles found in this well. This change is also relatively abrupt, occurring over 25-30 ft (8-10 m) of section at a subsurface depth of approximately 8850 to 8880 feet. The change may be located somewhat lower in the Frobisher-Alida interval than in the above well, but is still relatively high in the interval.

The stratigraphic distribution of lithofacies in NDGS 7207 (Fig. 7) is more difficult to interpret than in the previously discussed wells. The most restricted marine lithofacies (5, 6, 12) present in this well are only present in the Ratcliffe interval at the top of the cored interval (Fig. 2). There appears to be some stratigraphic separation of facies in the two cycles shown by the lack of the more restricted marine group of facies in the interval from approximately 9380 to 9500 feet subsurface. However, a portion of this interval coincides with a gap in available core and these relatively restricted marine lithofacies were reported as present in the missing core by Waters (1984). Thus, there is not any clear stratigraphic separation of lithofacies by cycle type present in this core as there is in wells 793 and 1262 (Fig. 6).

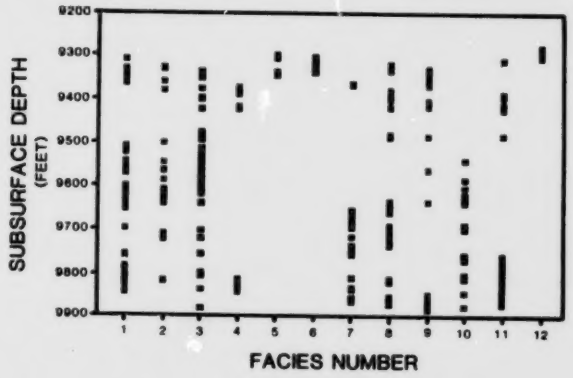


Fig. 7 Stratigraphic distribution (subsurface depth) of lithofacies 1 through 12 identified in core from NDGS 7207.

SUMMARY

Numerical analysis of cyclicity in the Mission Canyon and lower Charles Formations of the central Williston Basin of North Dakota successfully identified several types of cyclicity present in the sequence. These included two types of cyclicity involving relatively normal marine facies, oolitic-coated grain-pisoid cycles, and somewhat oscillatory cyclicity among various relatively restricted marine facies. The presence of Markov property was detected in all three units in this study. In each well, several lithofacies were found to be mutually substitutable or interchangeable within the succession. The significant transitions were resolved in all three wells into two mutually exclusive, non-interacting sets of Markov dependencies or cyclicity. The separate nature of the two types of cycles was also clearly displayed by plots of individual facies versus depth for two wells but not for a third. However, the third well also showed the least clear cyclic patterns. Entropy plots for all three wells suggest the presence of symmetric cyclicity.

CONCLUSIONS

1) Cyclicity is present in the Mission Canyon and lowermost Charles Formations of the central Williston Basin.

2) Although cyclicity has been determined to be present, at this state of the analysis individual cycles have not been identified nor cycle scale been determined.
3) Mutually substitutable lithofacies are present. The simplest but not the only interpretation of these is as adjacent depositional environments between the same distal and proximal environments. An example of such a situation might be shoal and intershoal facies between lagoon and shelf environments.
4) Relative entropy plots indicate that cyclicity is symmetrical. This is a common type of cyclicity in shallow carbonate sequences and can, for example, be produced by transgression-regression events or by migration along strike of shelf facies due to changes in local environmental conditions.
5) The distinct and independent nature of cycles identified by Markov and substitutability analyses, and the clear and abrupt change in dominant cycle type seen in two wells imply separate generating mechanisms for cycles in the upper and lower portions of the interval. Furthermore, since the upper cycle is composed of the more restricted marine facies in both of these wells, a sudden rather than gradual change in the depositional control is implied for the initiation of the more evaporitic conditions that characterize the upper Madison Group in the Williston Basin.

ACKNOWLEDGEMENTS

This research was assisted by a grant-in-aid of research from Sigma Xi, The Scientific Research Society, and by support from the Graduate School of the University of North Dakota and the North Dakota Geological Survey. Richard D. LeFever and Moira Campion provided valuable advice and assistance.

REFERENCES CITED

Davis, J. C., 1986, Statistics and data analysis in geology, 2nd ed.: New York, Wiley and Sons, 646p.

Elliott, T. L., 1982, Carbonate facies, depositional cycles, and the development of secondary porosity during burial diagenesis: Mission Canyon Formation, Haas Field, North Dakota, In: Christopher, J. E., and Kaldi, J. (eds.), Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication 6, p. 153-179.

Harris, S. B., Land, C. B., Jr., and McKeever, J. H., 1966, Mission Canyon stratigraphy, North Dakota: American Association of Petroleum Geologists Bulletin, v. 50, p. 2269-2276.

Hattori, I., 1976, Entropy in Markov chains and discrimination of cyclic patterns in lithologic successions: Journal of the International Association for Mathematical Geology, v. 8, p. 477-497.

Hohn, M. E., 1976, Binary coefficients: A theoretical and empirical study: Journal of the International Association for Mathematical Geology, v. 8, p. 137-150.

Lindsay, R. F., and Roth, M. S., 1982, Carbonate and evaporite facies, dolomitization and reservoir distribution of the Mission Canyon Formation, Little Knife Field, North Dakota, In: Christopher, J. E., and Kaldi, J. (eds.), Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication 6, p. 153-179.

Powers, D. W., and Easterling, R. G., 1982, Improved methodology for using embedded Markov chains to describe cyclical sediments: Journal of Sedimentary Petrology, v. 52, p. 913-923.

Shinn, E. A., and Robbin, D. M., 1983, Mechanical and chemical compaction in fine-grained shallow-water limestones: Journal of Sedimentary Petrology, v. 53, p. 595-618.

Sneath, P. H. A., and Sokal, R. R., 1973, Numerical taxonomy: San Francisco, W. H. Freeman and Co., 573 p.

Waters, D. L., 1984, Depositional cycles and coral distribution, Mission Canyon and Charles Formations, Madison Group (Mississippian), Williston Basin, North Dakota: M.Sc. Thesis, University of North Dakota, Grand Forks, 173p.

Worsley, N., and Fuzesy, A., 1978, The potash-bearing members of the Devonian Prairie Evaporite of southeastern Saskatchewan south of mining area, In: Montana Geological Society 24th Annual Conference, Williston Basin Symposium, Billings, Montana, p. 153-161.

Zeller, E. J., 1964, Cycles and psychology, In: Merriam, D. F. (ed.), Symposium on cyclic sedimentation: State Geological Survey of Kansas, Bulletin 169, p. 631-636.

DEPOSITIONAL CYCLES IN THE MISSISSIPPIAN MISSION CANYON LIMESTONE AND CHARLES FORMATION, WILLISTON BASIN, NORTH DAKOTA

DOUGLAS L. WATERS[1] AND WILLIAM J. SANDO[2]

ABSTRACT

Study of 29 cores from wells in the Mississippian Mission Canyon Limestone and Charles Formation (Madison Group) of western North Dakota resulted in recognition of five lithologic suites and two lithologic subsuites in each of three of these suites. These lithologic suites and subsuites represent the following depositional environments and subenvironments: I) Supratidal-intertidal environment having sabkha, tidal flat and evaporitic ponds, and lagoons; II) intertidal environment which can, in some places, be differentiated into subenvironment IIa, low-energy accumulations of tidal ponds, drowned tidal flats, and possibly lagoons, or subenvironment IIb, higher-energy accumulations of shoals and tidal channels; III) restricted marine environment; IV) transitional zone differentiated into subenvironment IVa, a transitional zone between the restricted marine environment and open-marine environment, or subenvironment IVb, a transitional zone between the intertidal environment and an open-marine environemnt; V) open-marine environment differentiated into subenvironment Va, low-energy open-marine environment, and Vb, higher-energy open-marine environment representing offshore shoals or submarine banks.

Three regressive carbonate cycles that correspond to the Tilston, Frobisher-Alida, and Ratcliffe intervals of the upper part of the Madison are recognized. Each cycle shows a similar sequence of lithology, beginning at the base with rocks deposited under open-marine conditions (V) and followed by rocks deposited in progressively shallower marine environments (IV, III, and II), culminating at the top with rocks deposited in intertidal and supratidal environments (II and I).

INTRODUCTION

The original purpose of this study was to determine the distribution and significance of corals for correlation in well cores from the Mississippian Mission Canyon Limestone and Charles Formation in western North Dakota (Waters and Sando, in press). Cores from more than 50 wells, including 29 (Fig. 1) described in foot-by-foot detail, were examined at the Wilson M. Laird Core and Sample Library of the North Dakota Geological Survey. A total of 6,274 ft of Madison core examined included 917 ft from the Ratcliffe interval, 3,745 ft from the Frobisher-Alida interval, 909 ft from the Tilston interval, and 703 ft from the Bottineau interval. Nine cores from the Poplar interval were examined but not described.

One facet of the coral study was to determine the relationship of coral distribution to depositional environments inferred from study of the lithology of the cores. Lithologic and petrographic studies, when placed in a stratigraphic context, revealed a cyclical sequence of environments that is the focus of this paper.

[1]ARCO Alaska, Inc.
Anchorage, Alaska 99510-0360

[2]U.S. Geological Survey
U.S. National Museum of Natural History
Washington, D.C. 20560

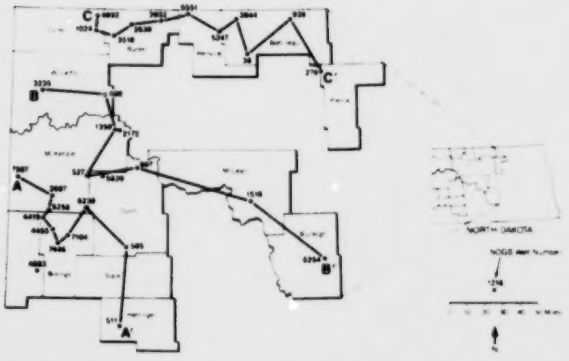


Fig. 1 Locations of wells from which cores were studied. Cores from NDGS Well Nos. 4683 and 5639 were not described. Cross-sections A-A', B-B', and C-C' constructed from this core study are shown on figures 9-11.

STRATIGRAPHY AND PALEOGEOGRAPHIC SETTING

The Williston Basin is an intracratonic basin that was part of a broad carbonate shelf during Mississippian time (Fig. 2). Mississippian sedimentation in the Williston Basin of western North Dakota is represented by approximately 1400-2300 ft of carbonate and evaporite strata assigned to the Madison Group.

This study uses the informal subsurface Madison terminology of the North Dakota Geological Survey (Smith, 1960; Anderson et al, 1960; Eastwood, 1961; Ballard, 1963; Carlson and Anderson, 1966) superimposed on formal Madison lithostratigraphic units; age relationships are inferred from coral biostratigraphic data (Fig. 3). We draw the Mission Canyon-Charles contact at the top of the Frobisher-Alida interval because this interval commonly contains the lowest extensive evaporite unit in Saskatchewan and North Dakota. The Lodgepole-Mission Canyon contact is placed at the top of the Bottineau interval.

PREVIOUS WORK

Previous studies of the upper part of the Madison Group in the Williston Basin produced depositional models that describe shallow-water carbonate environmental complexes. However, these studies did not recognize the essential cyclicity of the regressive carbonate sequence.

Edie (1958) described four major environments in the Mission Canyon and lower part of the Charles in southeastern Saskatchewan; they were, from offshore to onshore: (1) basin, (2) shelf and "bank" margin, (3) "bank," and (4) lagoon. The rock types he ascribed to the basin environment were represented by "dark brown-grey argillaceous limestones containing scattered white crinoid columnals, black bituminous

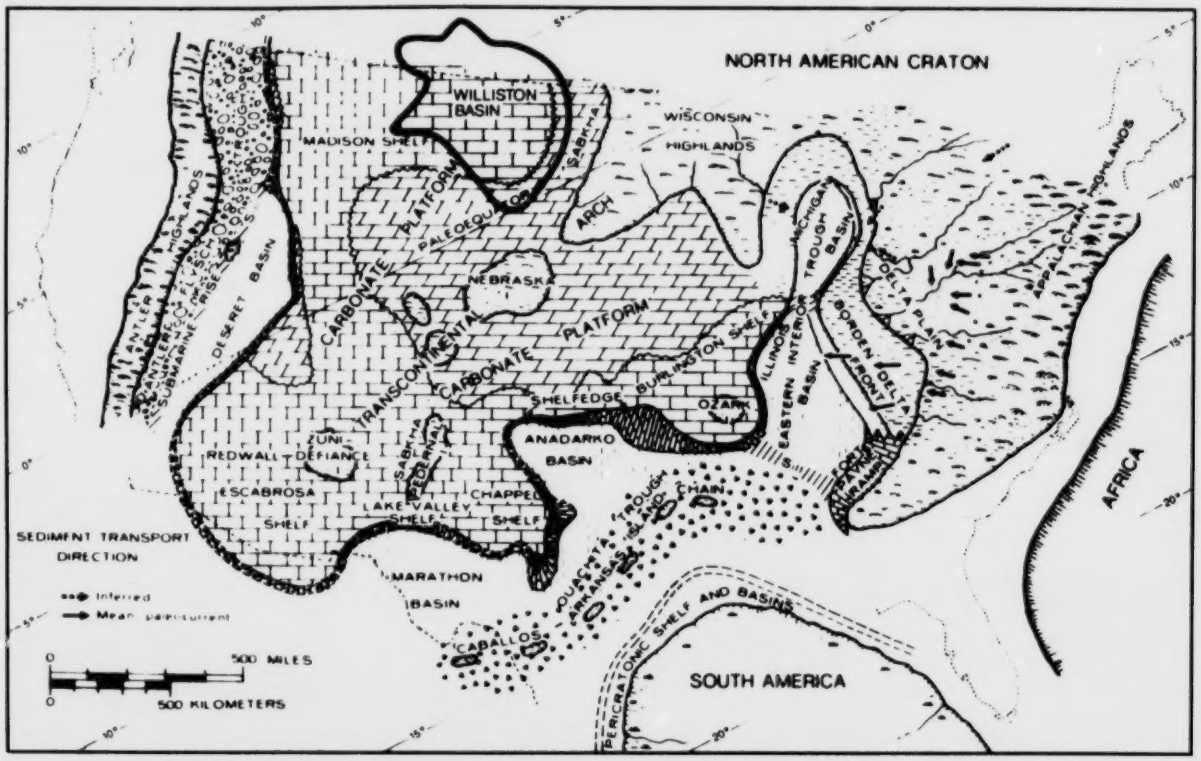


Fig. 2 Paleogeographic and lithofacies map of the conterminous United States during middle Mississippian time (from Gutschick and Sandberg, 1983, p. 84), showing location of Williston Basin.

shale partings and brownish grey chert." Rocks formed on the shelf and "bank" margin were composed of "cream-white fossiliferous-fragmental and chalky limestones containing crinoids, bryozoans, brachiopods and zaphrentid corals." Rocks from his "bank" environment consisted of "cream-white precipitated limestones including pisolitic, oolitic, pseudo-oolitic, and lithographic types" containing abundant algae and few scattered gastropods. The lagoon environment was said to be represented by "cream-white chalky argillaceous limestone containing ostracods, earthy to sucrosic secondary dolomite and anhydrite."

Edie (1958) also made several perspicacious interpretations of the rock types he observed. He found (p. 340) the color of "shelf-type" limestone to be light colored because the sediments were deposited in a shallow, well-oxygenated environment. In contrast, he found "basin-type" limestones to be darker, a result of organic carbonaceous sediments having disseminated pyrite deposited and preserved in a reducing (non-oxygenated) environment. Edie (p. 342) considered pisolites to be of algal origin, oolites to be chemically precipitated, and pseudo-oolites probably formed by a combination of these processes; he also recognized primary and secondary dolomite. Primary dolomite formed directly as an evaporite characterized by a cryptocrystalline habit and commonly intermixed and interbedded with anhydrite. Secondary dolomite possesses a sucrosic texture and intercrystalline porosity and commonly replaces skeletal material.

Irwin (1965) proposed three broad energy zones thought to occur in epeiric seas—zones X, Y, and Z. Zone X, a low-energy zone, was farthest offshore and extended for hundreds of miles. Zone Y was a high-energy zone where skeletal matter was winnowed and broken by wave and tidal action; it was tens of miles wide. Zone Z was a shallow, low-energy zone, tens to hundreds of miles wide. Irwin described six sedimentation zones associated with the three energy zones. He became aware of the sedimentation zones during his studies of Mississippian sedimentation patterns in North Dakota and South Dakota. Sedimentation zone I consisted of animal skeletal calcisiltite derived from adjacent shoreward zones. Zone II was composed of skeletal calcarenite. Zone III consisted of oolites, pseudoolites, peloids, and bioclastic carbonate. Zone IV was composed of primary chalky dolomite. Zone V consisted of evaporites. Zone VI was composed of algal mudstone, oolites and pelletoids, and represented a normally saline environment that had been freshened with river and rain water, which promoted abundant algal growth. Irwin claimed that three factors governed the width of the sedimentation zones: (1) climate, (2) barriers, and (3) slope of the sea floor.

Harris and others (1966) presented a depositional model for the upper Mission Canyon strata (Frobisher-Alida interval) of North Dakota that was very similar to that of Edie (1958). Four environments were recognized: basin, shelf, bank, and lagoon. The basin environment was characterized by formation of dark, argillaceous, fine-grained mudstone with rare fossils. The lithologies of the shelf environment consisted of light colored, fine- to coarse-grained, skeletal limestone with thin beds of oolitic and algal limestone containing crinoids, bryozoans, and corals. The lithology of the bank environment was composed predominantly of light colored, oolitic-pisolitic-algal limestone. The lithology of the lagoon environment was composed of anhydrite and evaporitic dolomite, with thin beds of oolitic limestone, shale, salt, and dolomitic limestone. Harris and others reported that the environments in north-central North Dakota migrated with time to the southwest and that this indicated a regression of the sea to the southwest.

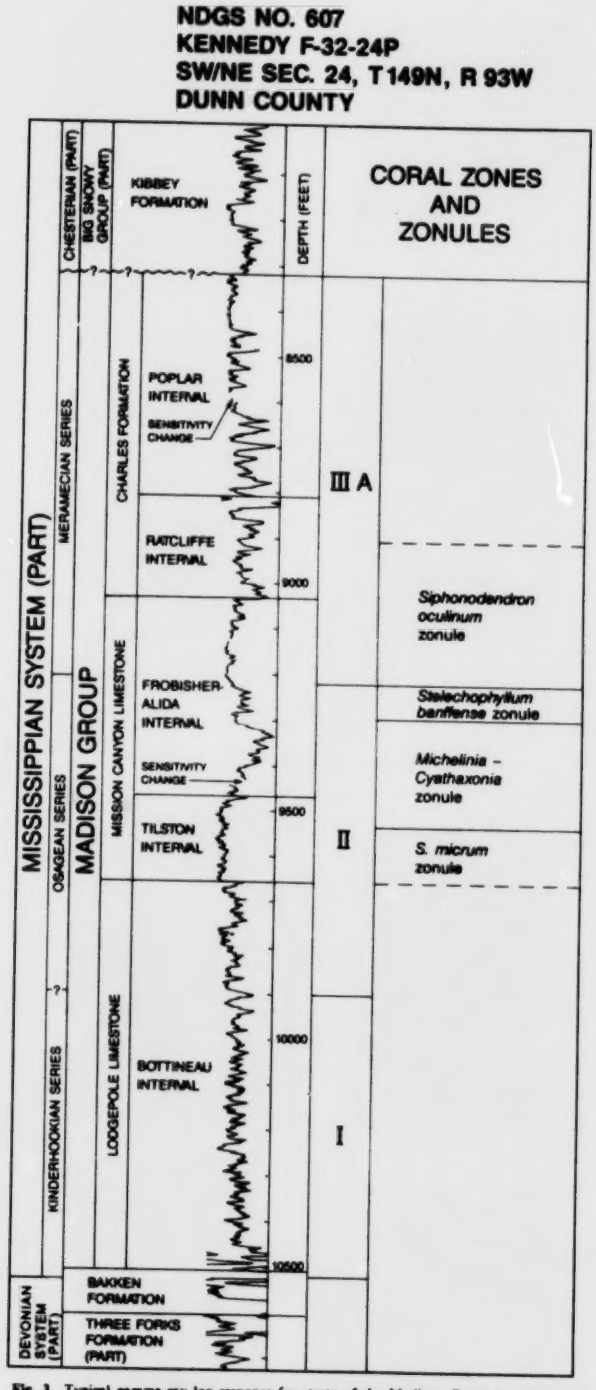


Fig. 3 Typical gamma-ray log response for strata of the Madison Group in west-cental North Dakota, showing informal, marker-defined, interval boundaries, formal rock units, ages, coral zones of Sando and Bamber (1985) (left column), and coral zonules of Waters and Sando (in press).

They also discussed the distribution of marker beds in the upper part of the Mission Canyon and suggested that the marker beds composed of terrigenous clastic material were deposited during abrupt, short-lived, transgressions of the sea.

Lindsay and Roth (1982) regarded the Mission Canyon of the Williston Basin as a regressive-upward, shoaling complex in an epeiric sea that was later covered by an advancing sabkha. Five subtidal environments and one intertidal-supratidal complex were distinguished in cores at the Little Knife field (Lindsay and Roth, 1982, fig. 4). Lindsay and Roth related their subtidal environments to Irwin's energy zones X, Y, and Z: (1) Low-energy, basin-marine environment represented by argillaceous, laminated, skeletal pelletal packstone grading into skeletal mudstone/wackestone corresponding to Irwin's energy zone X. (2) Open, shallow-marine environment represented by mudstone and skeletal wackestone interbedded with skeletal packstone/grainstone corresponding to part of energy zone Y. (3) Transitional, open to restricted marine environment represented by burrowed skeletal wackestone/dolowackestone and mudstone/dolomudstone corresponding to part of energy zone Y. (4) Restricted marine environment represented by mudstone and dolomudstone, part of Irwin's energy zone Z. (5) Marginal marine environment represented by skeletal wackestone and mudstone, part of energy zone Z.

Lindsay and Roth (1982) mentioned that intertidal buildups, composed of pisolitic-oolitic-peloidal-oncolitic and skeletal packstones, capped lithologies of the subtidal marine environment. Immediately behind and interfingering with the intertidal buildups they reported lagoonal rocks consisting of mudstone, algal laminated mudstone/dolomudstone, and anhydrite. There appears to be a slight discrepancy between the lithologies associated with Irwin's (1965) original high energy zone Y and those that were interpreted by Lindsay and Roth (1982). Irwin described oolites-pseudoolites and peloids in sedimentation zone III of high energy zone Y, which seem most similar to the lithology of Lindsay and Roth's intertidal buildup accumulations which they placed in low energy zone Z.

Elliott (1982) examined the "Glenburn zone" of the Mission Canyon in the Haas field and distinguished two separate facies: a cyclic, coated-grain facies and a peloidal, intraclastic facies. The cyclic, coated-grain lithofacies was reported to consist of skeletal wackestone and oolitic, pisolitic packstone/grainstone and was probably formed as a shoal. The peloidal, intraclastic lithofacies was said to consist of sparse skeletal wackestone/packstone, dolomite, and peloidal, interclastic packstone/grainstone with minor ooids and pisoids formed in a lagoon, sheltered behind the previously described pisolitic-oolitic shoal. Silty patterned dolomite, considered by Elliott to represent marker beds, was said to have been deposited in these lagoons during maximum restriction or desiccation prior to sabkha evaporite deposition.

LITHOLOGIC SUITES AND SUBSUITES

TERMINOLOGY

Rock names used in this study employ Dunham's (1962) textural classes (mudstone, wackestone, packstone, and grainstone). Attached to these textural classes are modifiers from names of grain types (pisolites, oolites, pseudoolites, peloids, oncolites, algae, and lithoclasts) or fossil types (crinoids, brachiopods, ostracods, gastropods, and foraminiferids). The term skeletal indicates unrecognizable fossil material. Bioturbation may be a major feature of the rocks and is indicated by the adjective burrowed. Hyphens separating grain or fossil types in rock names indicate that one, all, or any combination of fossil or grain types can occur in the various textural classes of Dunham (1962). For example, the rock name "pisolitic-oolitic packstone or grainstone" can be several different rock types, such as pisolitic packstone, oolitic packstone, or pisolitic

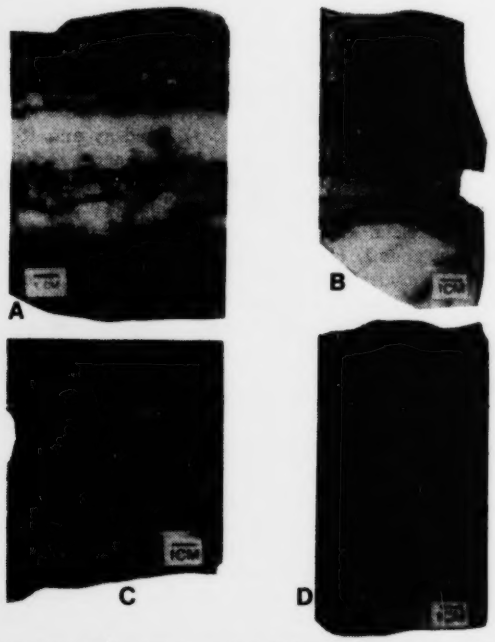


Fig. 4 Slightly etched, slabbed cores from Madison Group. A) Bedded, "chicken-wire" anhydrite, Suite I, Frobisher-Alida interval, NDGS Well No. 607 at 9,065 feet below KB. B) Stromotolitic mudstone and displacive nodular anhydrite, Suite I, Ratcliffe interval, NDGS Well No. 7207 at 9,307 feet below KB. C) Patterned mudstone, slightly dolomitic, Suite I, Frobisher-Alida interval, NDGS Well No. 607 at 9,269 feet below KB. D) Algal laminated mudstone and anhydrite, Suite I, Ratcliffe interval, NDGS Well No. 607 at 8,968 feet below KB.

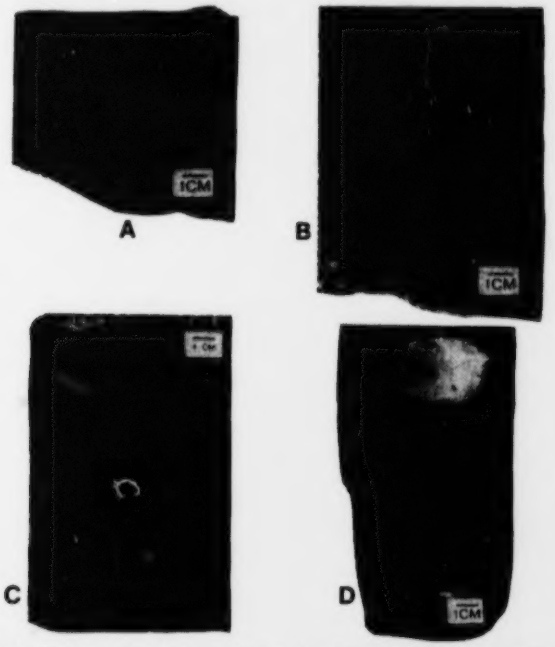


Fig. 6 Slightly etched, slabbed cores from Madison Group. A) Oolitic wackestone and packstone, Subsuite IIb, Frobisher-Alida interval, NDGS Well No. 607 at 9,229 feet below KB. B) Pisolitic-oolitic packstone and grainstone, Subsuite IIb, Frobisher-Alida interval, NDGS Well No. 607 at 9,113 feet below KB. C) Burrowed, slightly dolomitic mudstone with gastropods, Suite III, Ratcliffe interval, NDGS Well No. 607 at 9,011 feet below KB. D) burrowed skeletal wackestone with *Vesiculophyllum* (top) and *Syringopora* (near bottom), Subsuite IVa, Ratcliffe interval, NDGS Well No. 7207 at 9,380 feet below KB.

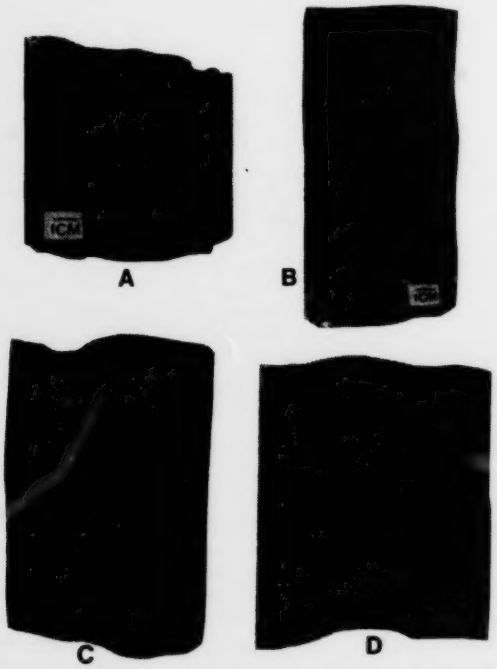


Fig. 5 Slightly etched, slabbed cores from Madison Group. A) Mudstone, slightly dolomitic, with porphyroblasts of anhydrite, Suite I, Frobisher-Alida interval, NDGS Well No. 4455 at 9,304 feet below KB. B) Peloidal-algal-oncolitic wackestone, Subsuite IIa, Ratcliffe interval, NDGS Well No. 7207 at 9,348 feet below KB. C) Peloidal-oncolitic and sparse skeletal wackestone, Subsuite IIa; Frobisher-Alida interval, NDGS Well No. 527 at 9,902 feet below KB. D) Peloidal-lithoclastic packstone and grainstone, Subsuite IIb, Frobisher-Alida interval, NDGS Well No. 3944 at 3,865 feet below KB.

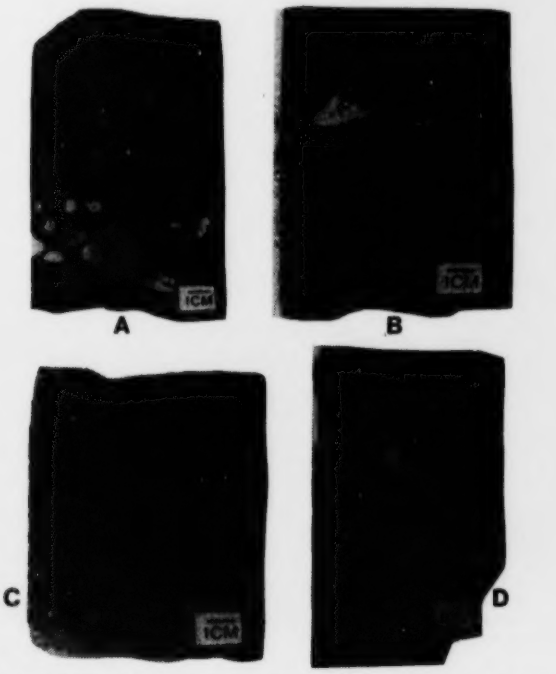


Fig. 7 Slightly etched, slabbed cores from Madison Group. A) Skeletal and peloidal wackestone containing *Vesiculophyllum* and red algae, Subsuite IVb, Frobisher-Alida interval, NDGS Well No. 607 at 9,305 feet below KB. B) Skeletal wackestone, Subsuite Va, Frobisher-Alida interval, NDGS Well No. 7207 at 9,661 feet below KB. C) Skeletal packstone and grainstone, Subsuite Vb, Tilston interval, NDGS Well No. 6230 at 10,049 feet below KB. D) Silicification of skeletal wackestone, Subsuite Va, Frobisher-Alida interval, NDGS Well No. 7207 at 9,744 feet below KB.

and oolitic packstone or any of these combinations of grain types in a grainstone. The order of abundance or dominance of grain types or fossil types decreases from left to right. In the rock name above, pisolites would be the more abundant grain type. The order of abundance of occurrence of textural classes also decreases from left to right. In the rock name above, packstone is the dominant textural class.

Because of the varied lithologies (Figs. 4-7), it was more convenient to group rock types into rock associations, here called lithologic suites and lithologic subsuites. Suites are lithologies of similar origin that can be distinguished from each other visually as well as stratigraphically. Five major lithologic suites designated with Roman numerals and six subsuites in three of these lithologic suites designated with letters (a) and (b) are recognized (Fig. 8). The lithologies most often observed are listed under each lithologic suite and subsuite in order of decreasing abundance. These lithologic suites, along with corals that were observed in cores, were plotted on three cross-sections (A-A', B-B', and C-C', Figs. 9-11).

DESCRIPTION

Lithologic Suite I

Lithologic suite I (Fig. 8) consists principally of anhydrite, dolomudstone and mudstone. The anhydrite may be massive, "chicken-wire", or layered (Fig. 4A). Dolomudstone or mudstone may be layered or massive and in some places it is displayed by nodular anhydrite (Fig. 4B) or is interlayered or laminated with anhydrite (Fig. 4D). Small porphyroblasts of anhydrite after gypsum may occur in the dolomudstone (Fig. 5A). Algal laminated mudstone and dolomudstone are recognized by their thin, irregular, discontinuous laminations (Fig. 4B and D). Discrete beds of peloidal-algal-ostracod mudstone or wackestone may also occur in this suite but are uncommon. Patterned dolostone containing disseminated pyrite and clastic material is commonly observed near the base of this lithologic suite (Fig. 4C). Burrows are uncommon. Gastropods are rare. In the eastern and southern portion of the study area, the Tilston interval is capped by lithologic suite I (Fig. 11). Lithologic suite I caps the Frobisher-Alida interval (Fig. 11); there it has a much greater distribution (occurs farther to the west) than it does in the preceding Tilston interval. Lithologic suite I in the Frobisher-Alida interval is also thicker in the east than it is in the Tilston interval (Fig. 11). Lithologic suite I occurs low in the Ratcliffe interval (Figs. 9, 10 and 11).

Lithologic Suite II

Lithologic suite II (Fig. 8) may be subdivided into two lithologic subsuites, IIa and IIb. In some places the lithologies from both subsuites are so intimately associated that the subsuite cannot be differentiated; where this is the case, the deposits are referred to merely as lithologic suite II.

Lithologic subsuite IIa (Fig. 8) is dominated by peloidal-algal-oncolitic wackestone or mudstone (Fig. 5 B and C) and is commonly interbedded with sparse skeletal wackestone or mudstone. Pisolitic-oolitic-peloidal wackestone or mudstone and stromatolitic limestone or dolostone may be present. This subsuite has a fauna composed solely of gastropods and ostracods, animals known to be eurytopic. Subsuite IIa occurs in the middle of the Frobisher-Alida interval (Figs. 9 and 10), in the upper part of the Frobisher-Alida interval (Fig. 11), and in the Ratcliffe interval (Figs. 9 and 10).

Lithologic subsuite IIb (Fig. 8) has more coated grains and less mud than subsuite IIa. Subsuite IIb is composed primarily of pisolitic-oolitic-peloidal packstone, grainstone, or wackestone (Fig. 6 A and B). Less common are: peloidal-algal-oncolitic-lithoclastic packstone or grainstone or wackestone (Fig. 5D), foraminiferid-pseudoolitic and rounded skeletal packstone or grainstone, stromatolitic limestone or dolostone, and skeletal wackestone. Gastropods are the most abundant fossils in subsuite IIb and are commonly accompanied by ostracods, foraminifera, corals, fragmented crinoids and brachiopods. A fenestral fabric is commonly observed in the rocks. Lithologic suit IIb is present in the Tilston interval (Fig. 9), in the lower part of the Frobisher-Alida interval (Fig. 10), and in the upper part of the Frobisher-Alida interval (Figs. 10 and 11).

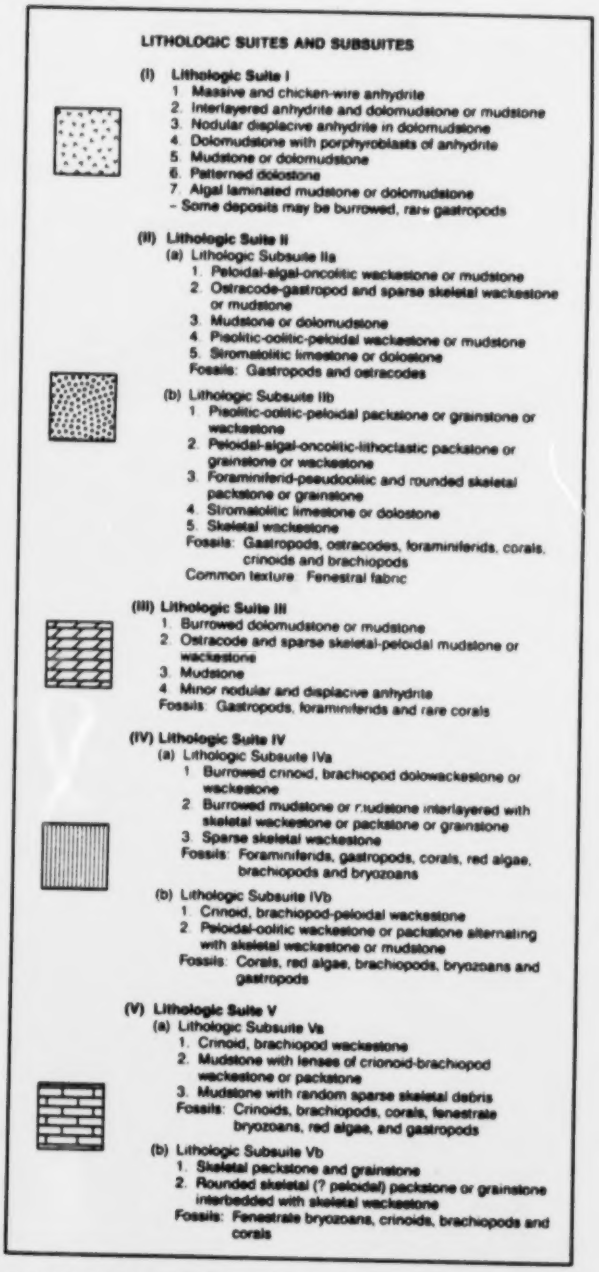

LITHOLOGIC SUITES AND SUBSUITES
(I) Lithologic Suite I
1. Massive and chicken-wire anhydrite
2. Interlayered anhydrite and dolomudstone or mudstone
3. Nodular displacive anhydrite in dolomudstone
4. Dolomudstone with porphyroblasts of anhydrite
5. Mudstone or dolomudstone
6. Patterned dolostone
7. Algal laminated mudstone or dolomudstone
- Some deposits may be burrowed, rare gastropods
(II) Lithologic Suite II
(a) Lithologic Subsuite IIa
1. Peloidal-algal-oncolitic wackestone or mudstone
2. Ostracode-gastropod and sparse skeletal wackestone or mudstone
3. Mudstone or dolomudstone
4. Pisolitic-oolitic-peloidal wackestone or mudstone
5. Stromatolitic limestone or dolostone
Fossils: Gastropods and ostracodes
(b) Lithologic Subsuite IIb
1. Pisolitic-oolitic-peloidal packstone or grainstone or wackestone
2. Peloidal-algal-oncolitic-lithoclastic packstone or grainstone or wackestone
3. Foraminiferid-pseudoolitic and rounded skeletal packstone or grainstone
4. Stromatolitic limestone or dolostone
5. Skeletal wackestone
Fossils: Gastropods, ostracodes, foraminiferids, corals, crinoids and brachiopods
Common texture: Fenestral fabric
(III) Lithologic Suite III
1. Burrowed dolomudstone or mudstone
2. Ostracode and sparse skeletal-peloidal mudstone or wackestone
3. Mudstone
4. Minor nodular and displacive anhydrite
Fossils: Gastropods, foraminiferids and rare corals
(IV) Lithologic Suite IV
(a) Lithologic Subsuite IVa
1. Burrowed crinoid, brachiopod dolowackestone or wackestone
2. Burrowed mudstone or mudstone interlayered with skeletal wackestone or packstone or grainstone
3. Sparse skeletal wackestone
Fossils: Foraminiferids, gastropods, corals, red algae, brachiopods and bryozoans
(b) Lithologic Subsuite IVb
1. Crinoid, brachiopod-peloidal wackestone
2. Peloidal-oolitic wackestone or packstone alternating with skeletal wackestone or mudstone
Fossils: Corals, red algae, brachiopods, bryozoans and gastropods
(V) Lithologic Suite V
(a) Lithologic Subsuite Va
1. Crinoid, brachiopod wackestone
2. Mudstone with lenses of crinoid-brachiopod wackestone or packstone
3. Mudstone with random sparse skeletal debris
Fossils: Crinoids, brachiopods, corals, fenestrate bryozoans, red algae, and gastropods
(b) Lithologic Subsuite Vb
1. Skeletal packstone and grainstone
2. Rounded skeletal (? peloidal) packstone or grainstone interbedded with skeletal wackestone
Fossils: Fenestrate bryozoans, crinoids, brachiopods and corals

Fig. 8 Lithologic suites and subsuites of Madison strata in the Williston Basin of North Dakota. Symbols are the same as those used in cross-sections A-A', B-B', and C-C' (Figures 9-11).

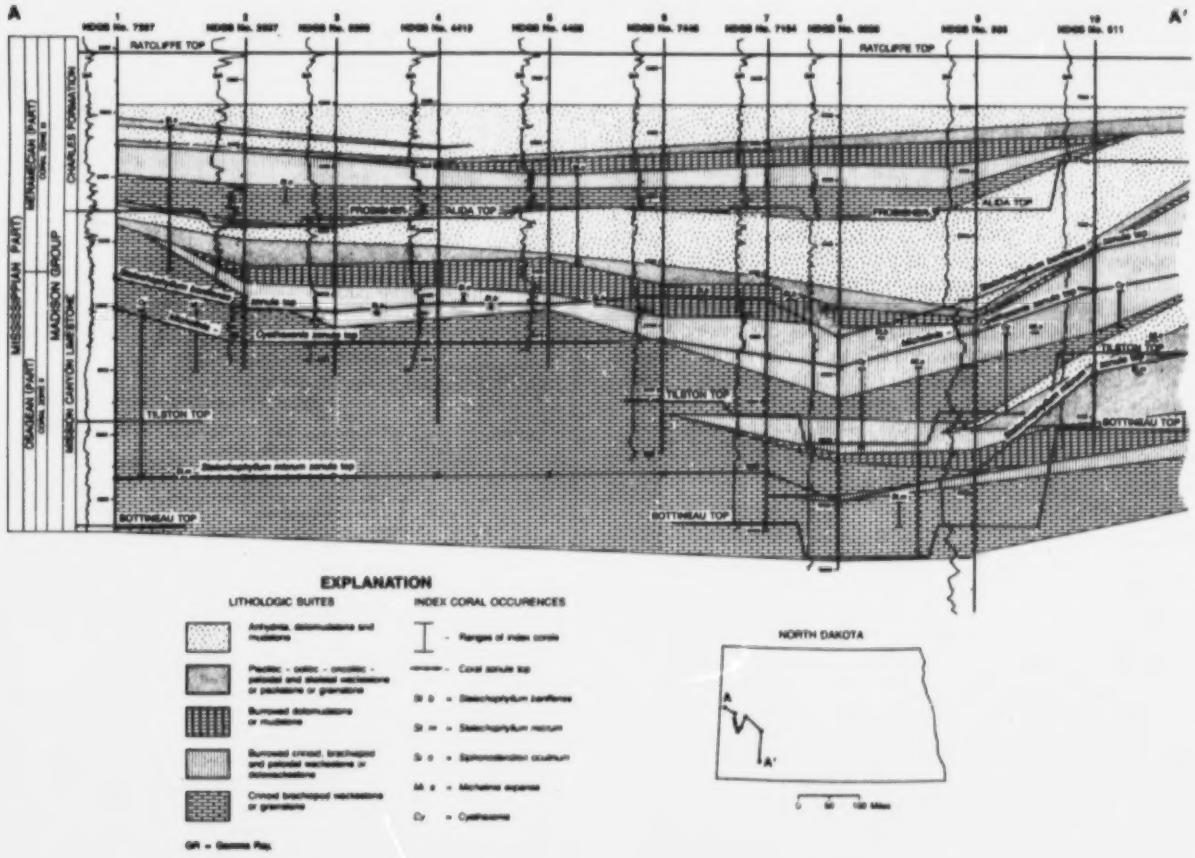


Fig. 9 Cross section A-A' in the Madison Group of North Dakota. See Table 1 for location of sections.

Table 1. Name and location of wells from which cores were studied.

Section Number	NDGS Well No.	Operator - Well Name	Location	County	Field
1	7397	Shell Oil Co. - Shell USA 42-28-43	SE NE 28-148-104	Mckenzie	Mondak
2	3997	Texaco Oil Co. - Gov't Mary Pace No. 1	SW NW 14-146-101	Mckenzie	Flat Top Butte
3	5258	Tiger Oil Co. - Roughrider Federal No. 3-32	SW NE 32-145-101	Mckenzie	Rough Rider
4	4419	Shell Oil Co. & N P Rwy Co. - Gov't No. 44-14	SE SE 14-144-102	Billings	Buckhorn
5	4455	Shell Oil Co. - Gov't No. 41s-18	NE NE 18-143-101	Billings	Elkhorn Ranch
6	7446	Tenneco Oil Co. - David USA No. 1-35	SE NE 35-142-101	Billings	Big Stack
7	7184	W H Hunt Trust Estate - Radakovich No. 1	SE SW 3-142-100	Billings	Tree Top
8	6230	Gulf Energy & Minerals Co. - Lind No. 2-13-2D	SW NE 13-145-98	Mckenzie	Little Knife
9	555	Socony Vacuum Oil Co. - Dvorak F-32-6P	SE NE 6-141-94	Dunn	wildcat
10	511	Socony Vacuum Oil Co. - Jacobs No. 1 F-16-24P	SW SW 24-134-96	Hettinger	wildcat
11	3230	Sun Oil Co. - State Lease No. 1	NW NW 16-156-101	Williams	wildcat
12	480	Amerada Petr. Corp. - Jens Kvam No. 4	NE SW 29-156-95	Williams	Beaver Lodge
13	1350	Amerada Petr. Corp. - Brenna-Lacey Unit No. 1	NE NE 1-152-95	Mckenzie	Antelope
14	527	California Oil Co. - Rough Creek Unit No. 1	NW NE 13-148-96	Mckenzie	wildcat
15	997	Mobil Oil Co. - Kennedy F-32-24P	SW NE 24-146-93	Dunn	wildcat
16	1518	Harmon Hansen Oil Syndicate - Samuelson No. 1	SE SW 32-146-82	McLean	wildcat
17	6254	Tom F. Marsh Co. - Clark No. 1	NW SW 10-140-76	Burleigh	wildcat
18	4682	Cardinal Petr. Co. - Orrin Lein 1-3417	SW SE 17-163-95	Divide	Kimberly
19	1284	Phillips Petr. Co. - Bradshaw No. 1	NE NW 29-152-99	Divide	Noonan
20	3518	Pan. Amer. Petr. Corp. - Cairns Dove No. 1	SW NW 12-161-94	Burke	wildcat
21	3630	Sun Oil Co. - A. Bloom No. 3	NE SE 3-162-92	Burke	Powers
22	3822	U.S. Smelting, Ref. & Mining Co. - Radenz "A" No. 1	SW NW 29-163-89	Burke	wildcat
23	5551	Kissinger Petr. Corp. - Knutson No. 14-1	SE SW 1-163-87	Renville	Pleasant
24	5247	Chandler & Associates Inc. - Crooks No. 15-25	SW SE 25-162-84	Renville	Mohall
25	3844	Chandler & Associates Inc. - Hallof No. 1	NE SW 21-163-82	Bottineau	N. Hope
26	36	California Oil Co. - Blanche Thompson No. 1	SW SE 31-160-81	Bottineau	wildcat
27	699	Lion Oil Co. - Einar Madsen No. 1	SE NW 27-163-77	Bottineau	wildcat
28	274	Phillips Petr. Co. - Olivia Sauda No. 1	NW SE 18-158-76	Pierce	wildcat

Undifferentiated sedimentary rocks of lithologic suite II occur in the Tilston, Frobisher-Alida, and Ratcliffe intervals (Figs. 9, 10, and 11).

Lithologic Suite III

Lithologic suite III (Fig. 8) is dominated by burrowed dolomudstone and mudstone (Fig. 6C). Less common lithologies are ostracod and sparse skeletal-peloidal mudstone or wackestone. Nodular, displacive anhydrite may be distributed randomly throughout these lithologies. Gastropods, foraminifers, ostracods, and rare corals are the only fossils in this lithologic suite. Lithologic suite III occurs in the Tilston, Frobisher-Alida, and Ratcliffe intervals and has a wide areal distribution (Figs. 9, 10, and 11).

Lithologic Suite IV

Lithologic suite IV is subdivided into two lithologic subsuites, IVa and IVb. Lithologic subsuite IVa is more common than IVb.

Lithologic subsuite IVa (Fig. 8) is dominated by burrowed crinoid, brachiopod dolowackestone (Fig. 6D). Mudstone or burrowed mudstone interbedded with skeletal wackestone or packstone or grainstone may also occur in this subsuite. Foraminifers and gastropods are common. Corals are more diverse and abundant in this subsuite than in the preceding suites. Red algae, brachiopods, and bryozoans may also be present. Subsuite IVa occurs in the Tilston, Frobisher-Alida, and Ratcliffe intervals (Figs. 9, 10 and 11).

Lithologic subsuite IVb (Fig. 8), commonly consists of crinoid, brachiopod-peloidal wackestone (Fig.7A), but may also contain peloidal-oolitic wackestone or packstone alternating with skeletal wackestone and mudstone. The most common fossils in this subsuite are corals and red algae. Brachiopods, bryozoans, and gastropods are less abundant. Subsuite IVb occurs in the Tilston interval (Fig. 11), the Frobisher-Alida interval (Fig. 10),and the Ratcliffe interval (Fig. 11).

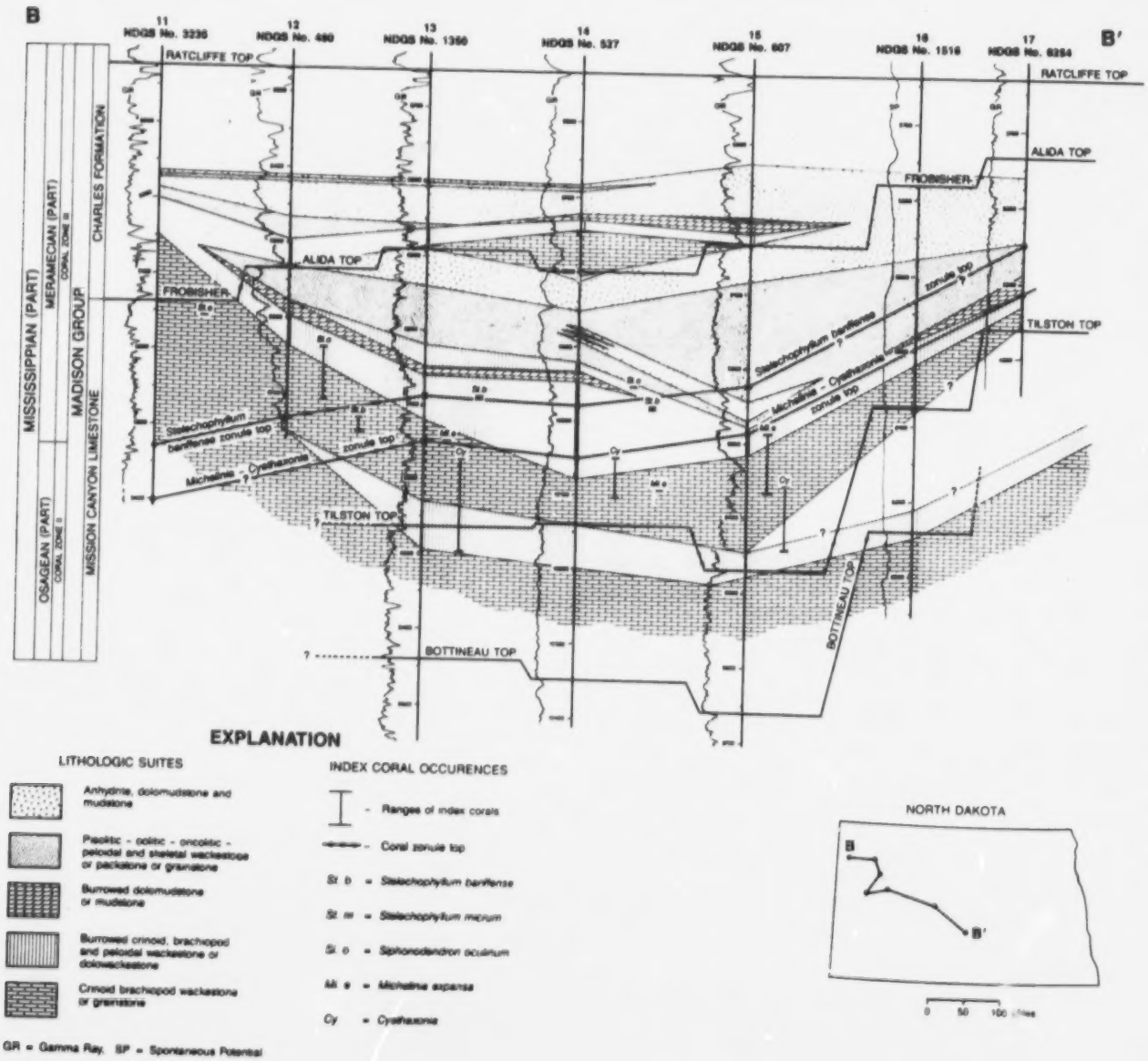


Fig. 10 Cross section B-B' in the Madison Group of North Dakota. See Table 1 for locations of sections.

Lithologic Suite V

Lithologic suite V is subdivided into two lithologic subsuites, Va and Vb. Lithologic subsuite Va is more common than Vb.

Lithologic subsuite Va (Fig. 8) consists primarily of crinoid, brachiopod wackestone (Fig. 7B). Other rock types that commonly occur in this subsuite are mudstones containing lenses of crinoid-brachiopod wackestone or packstone and mudstone containing random sparse skeletal debris. Subsuite Va contains a diverse and abundant assemblage of fossils: abundant crinoid fragments and brachiopods, diverse and abundant corals, common fenestrate bryozoans, and less common red algae and gastropods. Subsuite Va occurs in the Tilston, Frobisher-Alida, and Ratcliffe intervals (Figs. 9, 10 and 11).

Lithologic subsuite Vb (Fig. 8) ordinarily consists of coarse skeletal packstone or grainstone (Fig. 7C), but rounded skeletal (? peloidal) packstone or grainstone interbedded with skeletal wackestone may also occur. Fossils are usually fragmented; fenestrate bryozoans, crinoid fragments, and brachiopods are common and corals are small and rare. Subsuite Vb occurs in the Tilston interval (Figs. 9 and 11) and in the Frobisher-Alida interval (Fig. 11).

SILICIFICATION

Massive silicification of carbonate sediments is a major petrologic feature (Fig. 7D). Silicification appears to occur pervasively in lithologic suites III, IV, and V. It also appears to be stratigraphically controlled and occurs in the lower part of the Frobisher-Alida interval. The upper limit of silicification is at approximately the same stratigraphic interval (some 200 to

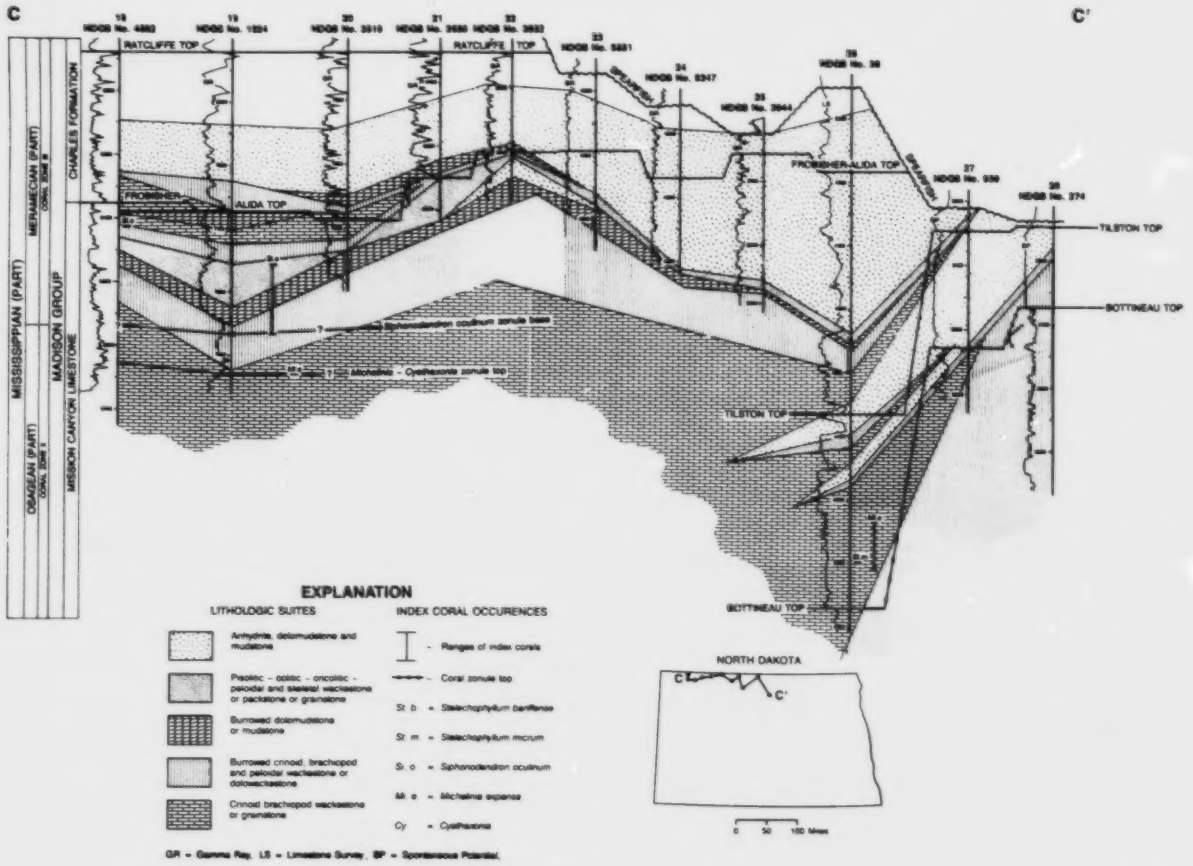


Fig. 11 Cross section C-C' in the Madison Group of North Dakota. See Table 1 for locations of sections.

300 feet) below the top of the Frobisher-Alida interval (Figs. 9 and 10). Hexactinellid sponge spicules may have provided the source for the silica in the sediments (Lindsay and Roth, 1982, p. 169), but the stratigraphic distribution of the silica and its complete dissolution were not explained by the present study.

DEPOSITIONAL ENVIRONMENTS AND SUBENVIRONMENTS

Five major depositional environments and six subenvironments are interpreted from the five lithologic suites and six subsuites of the Mission Canyon and lower part of the Charles in the Williston Basin of North Dakota (Fig. 12). A reconstruction of the depositional environments and subenvironments described below is illustrated in Figure 13.

DEPOSITIONAL ENVIRONMENT I

Lithologic suite I is interpreted as representing a supratidal-intertidal environment dominated by a sabkha bordered by a broad tidal flat having scattered evaporitic ponds and lagoons. Massive anhydrite and "chicken-wire" anhydrite probably formed in the sabkha, while layered anhydrite, nodular anhydrite, and laminated anhydrite and dolomudstone or mudstone formed subaqueously in evaporitic ponds and lagoons. Patterned dolostone and dolomudstone containing porphyroblasts of anhydrite after gypsum are commonly associated with these subaqueous anhydrites. Kendall (1983, p. 151, 154, and 155; Figs.9, 10, and 16) presented a similar environmental interpretation for "Frobisher Evaporite" of southeastern Saskatchewan. He considered layered and laminated anhydrites to form in evaporitic ponds and lagoons and mosaic anhydrite ("chicken-wire" anhydrite) or massive anhydrite to form in sabkhas bordering evaporitic ponds and lagoons. Algal laminated mudstones or dolomudstones containing rare peloids and oncolites formed on the tidal flats and possibly in the lagoons. Because of the very high salinities in these aqueous environments, fossils (other than algae) are rare. Only occasionally were waters fresh enough to support gastropods and ostracods.

DEPOSITIONAL ENVIRONMENT II

Lithologic suite II seems to represent an intertidal environment, divided into two subenvironments. Subenvironment IIa represents a low-energy, intertidal environment having tidal ponds and drowned tidal flats, and IIb represents a higher energy, intertidal environment characterized by shoals and tidal channels.

Elliott (1982, p. 140) also differentiated two separate "facies" (a "cyclic, coated-grain facies and a peloidal, intraclastic facies") for deposits with rounded grains in the Mission Canyon Limestone of northwestern North Dakota based on the microstructure of the grain types, packing of grains, and the amount of mud content. He considered "oolitic/pisolitic packstone and grainstone" to be deposited on shoals, and peloidal and intraclastic wackestone and packstone to be deposited in lagoons behind these shoals. Although we agree with Elliott's interpretation that pisolitic-oolitic packstone and

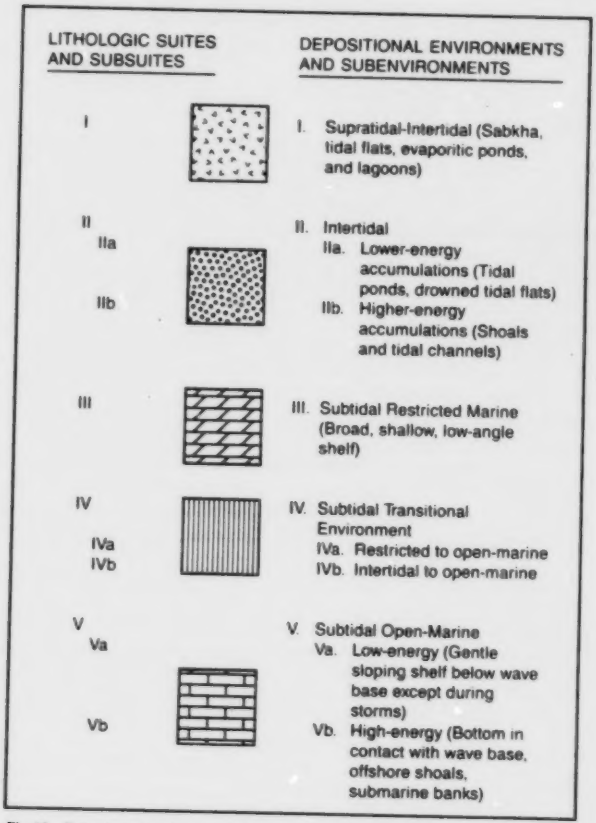


Fig. 12 Depositional environments and subenvironments of the Mission Canyon and lower part of the Charles interpreted from lithologic suites and subsuites shown in Figure 8. Symbols are the same as those used in cross-sections A-A', B-B', and C-C' (Figure 9-11).

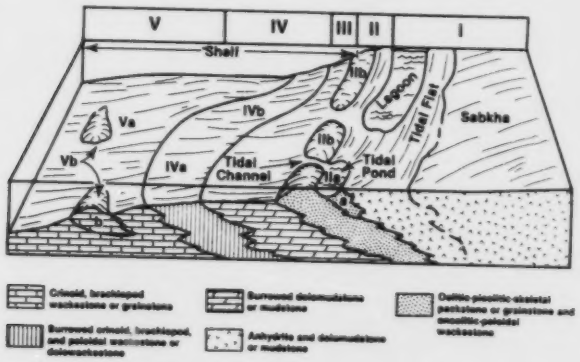


Fig. 13 Depositional model for the Mission Canyon and lower part of the Charles showing inferred depositional sites of lithologic suites and subsuites for the Williston Basin of North Dakota. Roman numerals and letters refer to lithologic suites and interpreted depositional environments as shown in Figures 8 and 12.

grainstone were likely deposited on shoals, we think that peloidal and intraclastic wackestone were probably deposited in water bodies smaller than lagoons (such as tidal ponds and drowned tidal flats), whose existence was more ephemeral than lagoons, as suggested by the sporadic occurrence of such wackestones in the Mission Canyon and lower part of the Charles of North Dakota.

Within subenvironment IIa, peloids and oncolites formed and algae grew in tidal ponds and drowned tidal flats and were, on occasion, covered by evaporite during times of hypersaline conditions. Occasionally, oolites and pisolites were swept in from the shoals (IIb) or were transported through tidal channels and deposited with sediments of lower energy wackestones and mudstones of tidal ponds and drowned tidal flats. Gastropods and ostracods thrived in the waters of this subenvironment.

Pisolites, oolites, and peloids of subenvironment IIb formed and accumulated in shoals and tidal channels in front of tidal ponds and tidal flats. This subenvironment was characterized by higher energy conditions and better marine circulation than existed in IIa. Deposits of subenvironment IIb can be distinguished from those of IIa, because they contain more coated grains, less mud, and often have fenestral fabric. A greater diversity of organisms is associated with deposits of subenvironment IIb; however, some of them are probably allochthonous. Numerous gastropods inhabited subenvironment IIb. Some corals were found in these deposits, primarily *Vesiculophyllum* (solitary) and morphogroups B and C of *Syringopora* (fasciculate) (Waters and Sando; this volume). *Vesiculophyllum* and *Syringopora* were commonly found relatively well preserved, indicating that they had not been transported. Other corals occurring less commonly in deposits of IIB are the solitary genera *Amplexizaphrentis* and *Sychnoelasma*, and *Stelechophyllum micrum* (massive colonial). Foraminifers were also found in subenvironment IIb, but they may have been transported from environment III, where they were abundant.

DEPOSITIONAL ENVIRONMENT III

Lithologic suite III was deposited on a broad, shallow, low-angle shelf where marine circulation and energy were greatly reduced and thus could be considered a restricted marine environment. The restriction of circulation probably was caused by the breadth and gentle slope of the bottom of this shelf. Bioturbated dolomudstones and mudstones typify the lithology formed in this restricted marine environment. Lindsay and Roth (1982, p. 156) also interpreted dolomudstones and mudstones that were extensively burrowed in the Mission Canyon of western North Dakota to represent a restricted marine environment. Peloidal and skeletal material were occasionally swept into this environment from the intertidal environment (II) during storms. Nodular anhydrite grew displacively in these deposits during periods of hypersalinity. A sparse fauna consisting primarily of gastropods, ostracods, and foraminifers could endure these restricted marine conditions. The rare occurrence of corals in deposits of environment III may indicate periods of less restriction. *Vesiculophyllum* (solitary) and morphogroups B and C of *Syringopora* (fasciculate) were ordinarily the only corals that occurred in this environment; however, the solitary *Sychnoelasma* and *Amplexizaphrentis*, the massive *Stelechophyllum banffense* , and the fasciculate *Siphonodendron oculinum* also were observed in deposits of environment III.

DEPOSITIONAL ENVIRONMENT IV

Lithologic suite IV formed in a transitional environment between shallow, marine sedimentation (III and II and "deeper", open-marine sedimentation (V). Two subenvironments are recognized. Subenvironment IVa represents a transitional environment between the restricted marine environment (III) and an open-marine environment (V). Lindsay and Roth (1982, p. 156) interpreted burrowed skeletal wackestone and dolomitic skeletal wackestone that succeed open-marine sedimentary rocks in the Mission Canyon in North Dakota to represent a transitional open- to restricted-marine environment.

Subenvironment IVb represents a transitional environment between an intertidal environment (II) and an open-marine environment (V). The slope of the shelf of environment III played a part in dictating which subenvironment of environment IV occurred. Where the shelf of environment III was steep, depositional environment III was reduced or absent. In this case, coated grains and peloids were swept off the shoals or out of the channels of environment II to become mixed with the skeletal debris and lime mud common in the more open waters. This resulted in peloidal-oolitic-skeletal wackestone or an interbedding of peloidal-oolitic wackestone with skeletal wackestone or mudstone. This "mixture" or interbedding of lithologies, otherwise more typical of environments II and V, was deposited in subenvironment IVb. Where there was a gentle slope in the area of environment III, formation of burrowed skeletal wackestones predominated, and subenvironment IVa existed.

Bioturbated skeletal wackestones and dolowackestones were the most common lithologies formed in subenvironment IVa. The subenvironment appears to have been somewhat restricted, but rocks formed here contain a more diverse fauna and greater amounts of skeletal debris than those formed in environment III. Gastropods and foraminifers are common in deposits of IVa. A diverse coral fauna consisting of the solitary corals *Vesiculophyllum, Sychnoelasma, Amplexizaphrentis, Cyathaxonia,* and *Lophophyllum* ; the fasciculate corals of *Syringopora* A, B, C, and D and *Siphonodendron oculinum* and the massive corals *Stelechophyllum banffense, S. micrum* , and *Michelinia expansa* inhabited subenvironment IVa. Red algae, brachiopods, and bryozoans also lived here. At times the environment became less restricted (perhaps the result of rising sea levels), and skeletal wackestone or packstone was deposited.

Subenvironment IVb fluctuated between intertidal and open-marine sedimentation as indicated by crinoid brachiopod-peloidal wackestone and peloidal-oolitic wackestone or packstone interbedded with skeletal wackestone. Abundant fragmented red algae and corals in subenvironment IVb indicate a subenvironment of higher energy and better marine circulation than for IVa. The corals in subenvironment IVb were mostly the solitary genera *Vesiculophyllum* and *Sychnoelasma* . The absence of other types of corals in this subenvironment indicates that IVb was a less favorable habitat for corals than IVa.

DEPOSITIONAL ENVIRONMENT V

Lithologic suite V was formed in an open-marine environment divided into two subenvironments. Subsuite Va represents low-energy deposits formed below wave base on a gently sloping shelf, and subsuite Vb represents a higher energy subenvironment where submarine banks and offshore shoals brought the bottom above the level of wave base.

Crinoid-brachiopod wackestone is the dominant lithology formed in subenvironment Va, but mudstones with sparse skeletal debris were also formed in this subenvironment. Lindsay and Roth (1982, p. 155) considered skeletal wackestone and mudstone of the Mission Canyon of North Dakota to be deposited below wave base in a shallow, low-energy open-marine setting. Subenvironment Va was usually below wave base except during storm activity. Storm deposits are recognized by lenses or layers of coarse skeletal debris (packstones and grainstones) surrounded by a lithology with greater mud content. This subenvironment favored a diverse fauna of fenestrate bryozoans, corals, and brachiopods. Subenvironment Va must have been the most hospitable subenvironment for corals as reflected by their higher diversity and greater abundance in this subenvironment than in any other. The coral fauna consisted of the solitary genera *Vesiculophyllum, Sychnoelasma, Amplexizaphrentis, Cythaxonia, Lophophyllum,* , and *Amplexocarinia* ; massive *Stelechophyllum banffense, S. micrum* and *Michelinia expansa* , and fasciculate *Syringopora* , A, B, C, and D.

The higher energy, open-marine subenvironment Vb consisted of submarine banks and offshore shoals. Deposits of this subenvironment are represented by extremely coarse skeletal grainstones and packstones whose fragments accumulated as a result of storm, wave, and possibly current activity. These accumulations must have been mostly above wave base. Lindsay and Roth (1982, p. 155) also considered skeletal packstones and grainstones of the open-marine environment to be deposited when the bottom came within wave base. A diverse fauna similar to that of Va was observed, but the skeletal matter is so fragmented that it probably represents accumulations of non-living organic material. Only a few, immature individuals (found as well preserved specimens) of the coral genera *Vesiculophyllum, Amplexizaphrentis* , and *Sychnoelasma* could tolerate such a turbulent environment.

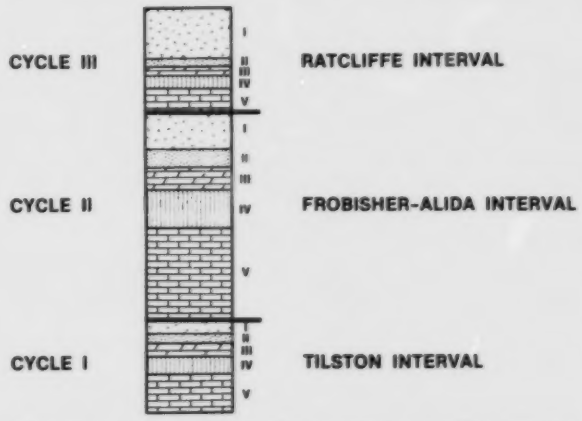


Fig. 14 Depositional cycles of the Mission Canyon and lower part of the Charles and marker-defined intervals in the Williston Basin of North Dakota. Roman numerals and symbols refer to lithologic suites and interpreted depositional environments as shown in Figures 8 and 12.

DEPOSITIONAL CYCLES

Three major regressive sequences of cycles, corresponding to the Tilston, Frobisher-Alida, and Ratcliffe intervals, are recognized in the Mission Canyon and lower part of the Charles Formations. The three cycles (Fig. 14) display a similar sequence of rock associations or lithologic suites; these are interpreted as representing depositional environments becoming progressively shallower and eventually ending with intertidal to supratidal deposition. The onset of each cycle began with open-marine sediments (depositional environments Va or Vb) on top of supratidal-intertidal sediments (depositional environment I) of the previous cycle. Evidence for this abrupt change in depositional environments is observed, for example, near the contact of the Tilston interval with the Frobisher-Alida interval (Figs. 9, and 11). Similar evidence for abrupt change is also observed near the contact of the Frobisher-Alida interval with the Ratcliffe interval; however, the change may be less abrupt, with a thin unit from environment II or IV intervening between those deposited in environments I and V (Figs. 9 and 10). In each cycle, deposits of progressively shallower depositional environments, IV, III,

and II, occurred on top of deposits of environment V, and the cycle eventually culminated with deposits from supratidal-intertidal conditions of environment I (Figs. 9, 10, and 11).

In cycle I the supratidal-intertidal sediments (depositional environment I) capping the Tilston interval were thin and restricted to the east (NDGS Well Nos. 505 and 511 in section A-A', Fig. 9) while more open marine sediments (IV and V) occurred in the west (NDGS Well Nos. 7207 and 6230 in section A-A', Fig. 9). In subsequent cycles (II and III, Frobisher-Alida and Ratcliffe), sediments of depositional environment I were thicker (Figs. 9, 10, and 11) and extended farther to the west (Figs. 9 and 10) than they did in the Tilston cycle. This indicates that the overall retreat of the sea was westward toward the basin center. This evidence agrees with Wilson's (1975, p. 283) interpretation that during later Madison time the sea had undergone a major regression westward.

ACKNOWLEDGEMENTS

This paper is an outgrowth of a thesis submitted by Waters for the M.Sc. degree at the University of North Dakota. We thank Drs. F.D. Holland, Jr., A.M. Cvancara, and J.R. Reid of the University of North Dakota for early guidance of the project. We are also grateful to S.B. Anderson of the North Dakota Geological Survey, R.F. Lindsay of Gulf Oil Exploration and Production Company, J.C. Pol and P.K. Mescher of Arco Exploration Company, and D.M. Petty of Tenneco Oil Exploration and Production Company for helpful discussions and suggestions during laboratory studies. Tenneco Oil Exploration and Production Company and Arco Exploration Company provided generous grants to support the laboratory studies. The North Dakota Geological Survey provided facilities and equipment for core examination. The paper was reviewed by J.W. Pierce and Ian MacIntyre.

REFERENCES CITED

Anderson, S.B., Hansen, D.E., and Eastwood, W.P., 1960, Subsurface studies, In: Oil fields in the Burke County area, North Dakota: North Dakota Geological Survey Report of Investigations no. 36, p. 1-25.

Ballard, F.V., 1963, Structural and stratigraphic relationships in the Paleozoic rocks of eastern North Dakota: North Dakota Geological Survey Bulletin no. 40, 42 p.

Carlson, C.G., and Anderson, S.B., 1966, A look at the lower and middle Madison of northwestern North Dakota: North Dakota Geological Survey Report of Investigations no. 43, 14 p.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, In: Ham, W.E., ed., Classification of carbonate rocks—a symposium: American Association of Petroleum Geologists Memoir 1, p. 108-121.

Eastwood, W.P., 1961, Maps of the Frobisher-Alida interval in North Dakota: North Dakota Geological Survey Report of Investigations 37, 3 pls.

Edie, R.W., 1958, Mississippian sedimentation and oil fields in southeastern Saskatchewan, In: Goodman, A.J., ed., Jurassic and Carboniferous of western Canada: Tulsa, American Association of Petroleum Geologists, John Andrew Allan Memorial Volume, p. 331-363.

Elliott, T.L., 1982, Carbonate facies, depositional cycles and the development of secondary porosity during burial diagenesis, In: Christopher, J.E., and Kaldi, J., eds., Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication No. 6, p. 131-151.

Fuzesy, L.M., 1960, Correlation and subcrops of the Mississippian strata in southeastern and south-central Saskatchewan: Saskatchewan Department of Mineral Resources Report No. 51, 63 p.

Gutschick, R.C., and Sandberg, C.A., 1983, Mississippian continental margins of the conterminous United States, In: Stanley, D.J., and Moore, G.T., eds., The shelfbreak: Critical interface on continental margins: Society of Economic Paleontologists and Mineralogists Special Publication No. 33, p. 79-96.

Harris, S.B., Land, C.B., Jr., and McKeever, J.H., 1966, Mission Canyon stratigraphy, North Dakota: American Association of Petroleum Geologists Bulletin, v. 50, p. 2269-2276.

Irwin, M.L., 1965, General theory of epeiric clear water sedimentation: American Association of Petroleum Geologists Bulletin, v. 49, p. 445-459.

Kendall, A.C., 1983, Continental and supratidal (sabkha) evaporites, No. 13, In: Walker, R.G., ed., Facies models: Geoscience Canada, Reprint Series 1, Fifth Printing, p. 145-157.

Lindsay, R.F., and Roth, M.S., 1982, Carbonate and evaporite facies, dolomitization and reservoir distribution of the Mission Canyon Formation, Little Knife Field, North Dakota, In: Christopher, J.E., and Kaldi, J., eds., Fourth International Williston Basin Symposium: Saskatchewan Geological Society, Special Publication No. 6, p. 153-179.

Sando, W.J., and Bamber, E.W., 1985, Coral zonation of the Mississippian System in the Western Interior Province of western North America: U.S. Geological Survey Professional Paper 1334, 61 p.

Saskatchewan Geological Society, 1956, Report of Mississippian Names and Correlations Committee: Regina, Saskatchewan.

Smith, M.H., 1960, Revised nomenclature for the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 44, no. 6, p. 959-960.

Waters, D.L., and Sando, W.J., this volume, Corals from the Madison Group, Williston Basin, North Dakota: Fifth International Williston Basin Symposium.

Waters, D.L., and Sando, W.J., in press, Coral zonules: New tools for petroleum exploration in the Mission Canyon Limestone and Charles Formation, In: Peterson, J.A., ed., Williston Basin: Exploration Model for a Cratonic Petroleum Province: American Association of Petroleum Geologists Memoir.

Wilson, J.L., 1985, Carbonate facies in geologic history: New York, Springer-Verlag.

A RECONNAISSANCE SEDIMENTOLOGICAL STUDY OF THE MIDDLE JURASSIC UPPER SHAUNAVON FORMATION, SOUTHWEST SASKATCHEWAN

R.C.L. WILSON

Department of Earth Sciences
The Open University Milton Keynes, MK7 6AA,
England

ABSTRACT

The Upper Shaunavon (15-25 m) is a mixed siliciclastic - carbonate unit. In the Rapdan and Dollard oilfield areas the lower part consists of quartz sands, calcareous shales, skeletal/peloidal packstones and grainstones that probably represent reworked relict sediments of a transgressive barrier island system. In the Instow - Bone Creek area the lower part is dominated by skeletal and ooid grainstones, some of which are producing reservoirs. Reservoir beds in the middle and upper parts consist of quartz and skeletal sands. Their porosity is enhanced by aragonite dissolution, and early freshwater phreatic calcite cement fringes ensured that little reduction of porosity occurred due to compaction during burial. Dolomitic sediments beneath, and on the flanks of reservoir units may have partially originated in the fresh - marine mixing zone, but some show features suggestive of an evaporative origin. The results of this study are consistent with earlier interpretations that envisage a NNE - SSW trending coastal barrier system. However, further detailed study of slabbed cores is needed to establish the extent to which wave and tidal processes sculptured Shaunavon reservoir units.

INTRODUCTION

Today, the industry view of the depositional environment of the upper part of the Shaunavon Formation (Godkin, personal communication, 1984) has much in common with published conclusions (Christopher, 1964; McMillan, 1966), namely a belt of shelf and shallow marine sands trending NNE-SSW, traversed by tidal channels, and forming a barrier protecting lagoons to the west beyond which occur "blanket" or "fluviatile" sands.

This paper reviews the evidence available concerning the lithofacies distribution of the Upper Shaunavon in the light of modern sedimentological knowledge concerning shoreline and shallow shelf sea sediments. A total of 40 cored sections through the Shaunavon Formation were examined, and samples taken for more detailed petrographic examination. The study is inevitably biased towards cores taken in producing fields, but an attempt was made to obtain some coverage between the fields, as well as to the east and west of the oilfield trend. The location of the wells studied is shown in Fig. 1. In addition, the thin section collection at Saskatchewan Energy and Mines' Subsurface Geological Laboratory in Regina was studied.

The Shaunavon oilfield trend is situated in the northwest quadrant of the Williston Basin. According to Christopher (1964), the Formation "strikes northeast and dips southeast 13 to 16 feet per mile into the Shaunavon Syncline across an irregular step-like monocline" (p.3). The oilfields are situated along this north-south trending monocline, but McMillan (1966) suggested that in the Rapdan field, entrapment of the oil is essentially stratigraphic, "as the height of the oil column exceeds that of the structure."

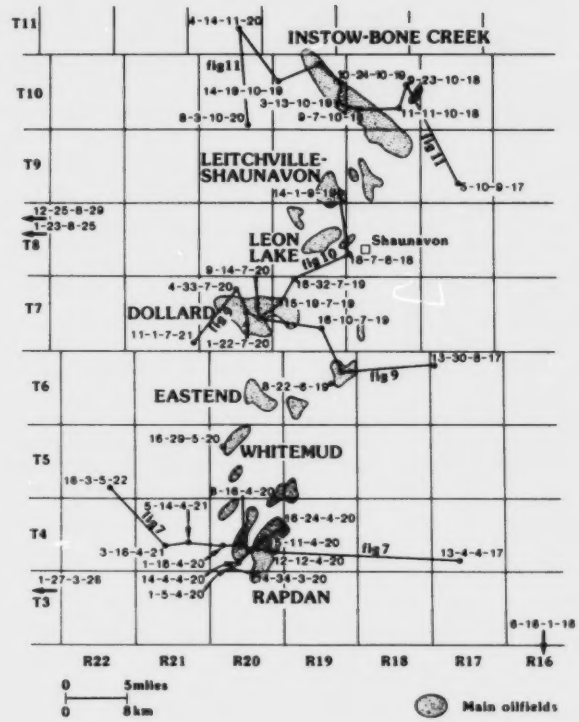


Fig.1 Map showing the location of wells studied.

GEOLOGICAL SETTING

In a recent review of the Jurassic of the Canadian western interior, Poulton (1984) showed the Shaunavon Formation as Late Bajocian - Early Bathonian in age, in which case the Upper Shaunavon is probably Early Bathonian. Poulton's generalized facies maps for the Bajocian and Bathonian indicate that the Shaunavon sea was connected to the epicontinental seaway to the west, although the Sweetgrass Arch was a positive area over which Jurassic strata thinned significantly. If there was such a connection during the Middle Jurassic, then it is probable that the Williston "sea" at this time was affected by tidal currents as it was during the Late Jurassic (see review by Bridges, 1982).

Given the overstep of Jurassic formations around the margin of the Williston Basin shown by Poulton (1984), it is probable that large areas bordering it during the Middle Jurassic comprised outcrops of Upper Paleozoic carbonates. If this was the case, the amount of siliciclastic influx into the

Williston Basin would have been relatively low, but windblown carbonate detritus might also be expected to have contributed significantly to the sediments, as is the case today along the southern margins of the Arabian Gulf.

Christopher's (1964, Fig. 22) isopachous map of the Upper Shaunavon shows a general thickening of the unit to the SE which may indicate that the paleoslope at the time was inclined gently in the same direction. Superimposed on this trend, Christopher showed a region of more complex variations in thickness which coincides with the NNE-SSW oil field trend. This second order pattern may partly be artificial due to the abundance of well data in this region in contrast to much greater well spacings elsewhere. It may also be due, as McMillan (1966) implied, to an irregular top - Lower Shaunavon topography caused by pre-Upper Shaunavon erosion. If such a topography exists, then it would have exerted a considerable influence on the lithofacies distribution within the Upper Shaunavon. The control of sea-bottom topography on the nature and geometry of deposits deposited by Holocene transgressions has been demonstrated in many parts of the world, so it is likely that similar effects were operative during the deposition of the Upper Shaunavon.

PRINCIPAL LITHOLOGIES

The main rock types identified in the Upper Shaunavon are tabulated below:

SILICICLASTICS	*Sandstones*	○ with large scale cross stratification
	Mixed Sandstones and shale	○ wavy bedded ○ bioturbated
	Shales	
CARBONATES	*Dolomites**	○ dolomitic mudstones ○ dolomitic sandstones ○ dolomitic limestones
	*Limestones**	○ peloidal packstones ○ ooid packstones and grainstones ○ skeletal sands (a spectrum ranging from wackestones to grainstones) ○ oncolitic packstones and grainstones (see Christopher, 1964, Fig. 17) ○ micrites

* All limestones, and most dolomites contain varying amounts of fine grade siliciclastic sand.

SANDSTONES

Irrespective of the sedimentary structures present, sandstones consist of moderately to well sorted fine sand (0.2 mm), dominated by quartz grains, which are subangular to subrounded. They range from entirely uncemented varieties, to sands with patchy calcite cements that seeded off scattered skeletal grains. Many non-porous sandstones either contain a fine grained dolomite matrix, or an admixture of clay. SEM studies reveal that many sandstones contain grains that exhibit varying quartz overgrowths, particularly where carbonate matrices are absent, or poorly developed, as in many reservoir sands (see Fig. 2). The paucity of slabbed cores rendered detailed study of the sedimentary and biogenic structures difficult, so the simple tri-partite division of sandstones tabulated above was adopted when compiling logs of the sequences. Sandstones in the Upper Shaunavon form the end member of two spectra of sediments leading to dolomitic sediments and the various types of limestone tabulated above.

MIXED SANDSTONES - SHALES

Although the proportion of sandstone and shale in parts of the Upper Shaunavon is quite variable, in the absence of slabbed cores, no attempt was made to make detailed divisions such as those suggested by Reineck and Singh (1973). Most heterolithic sequences studied were dominated by wavy or lenticular bedding, and to aid speed of logging during this reconnaissance study, they were grouped as one lithofacies. Rare examples of wave ripples were seen, and several examples of wavy/lenticular bedded units exhibiting low angle master bedding, probably due to later accretion, were observed.

SHALES

Following McMillan (1966), no attempt was made to record subtle differences between different types of shale based on colour. After initially recognizing six different categories, he found a division into calcareous, non-calcareous and red shales was a more practical definition. During this study, the majority of shales were found to be calcareous, and examples of shales that swelled when wetted were also quite common. As noted by McMillan, the non-calcareous and red shales contain slickensides; the present author believes these probably to be the result of pedogenic processes.

A few samples of dark grey green shales from the base of the Upper Shaunavon were collected to assess their petroleum source rock potential. TOC values ranging from 0.4 to 0.8 per cent were obtained, confirming the impression gained from core examination that these shales are lean.

DOLOMITES

Dolomitic mudstones and sandstones usually occur as interlaminated deposits (see Fig. 3C, D). Under the SEM the mudstones usually exhibit idiotopic dolomite rhombs up to 10 mm across. One example of laminated dolomitic mudstone with a brecciated interval was observed (Fig. 3F). In core descriptions, Christopher (1966) noted contorted intervals in several dolomitic units. Dolomitic sandstones contain similar dolomite crystals, although in a few cases larger crystals are present which clearly formed as cement (Fig. 4). Frequently, the quartz grains are seen floating in the dolomitic matrix, or quartz rich laminae are separated by dolomitic mudstone layers. In hand specimen, various combinations of dolomitic sandstones and mudstones can be seen:

(i) laminated sediments in which quartz rich layers show slight crenulations (Fig. 3A). The origin of these features is uncertain, but the possibility that they formed as wind (adhesion) ripples cannot be ruled out;

(ii) drapes over ripples within ooid grainstones;

(iii) mottled sediments (Fig. 3B) due either to bioturbation or perhaps by adhesion ripples.

Dolomitic limestones consist of three main types:

(1) grainstones with an early (pre-compaction) drusy dolomite fringe, where the dolomite clearly developed as a cement (Fig. 5F);

(2) dolomite partially replacing allochems, the packing of which suggests an original mud supported fabric, in which case the dolomite has also replaced an original matrix;

(3) packstones and wackestones with a dolomitic mudstone matrix, but showing no dolomitization of allochems (Fig. 5G, H);

(4) dolomitic micrites (i.e. micrite only partially replaced by dolomite).

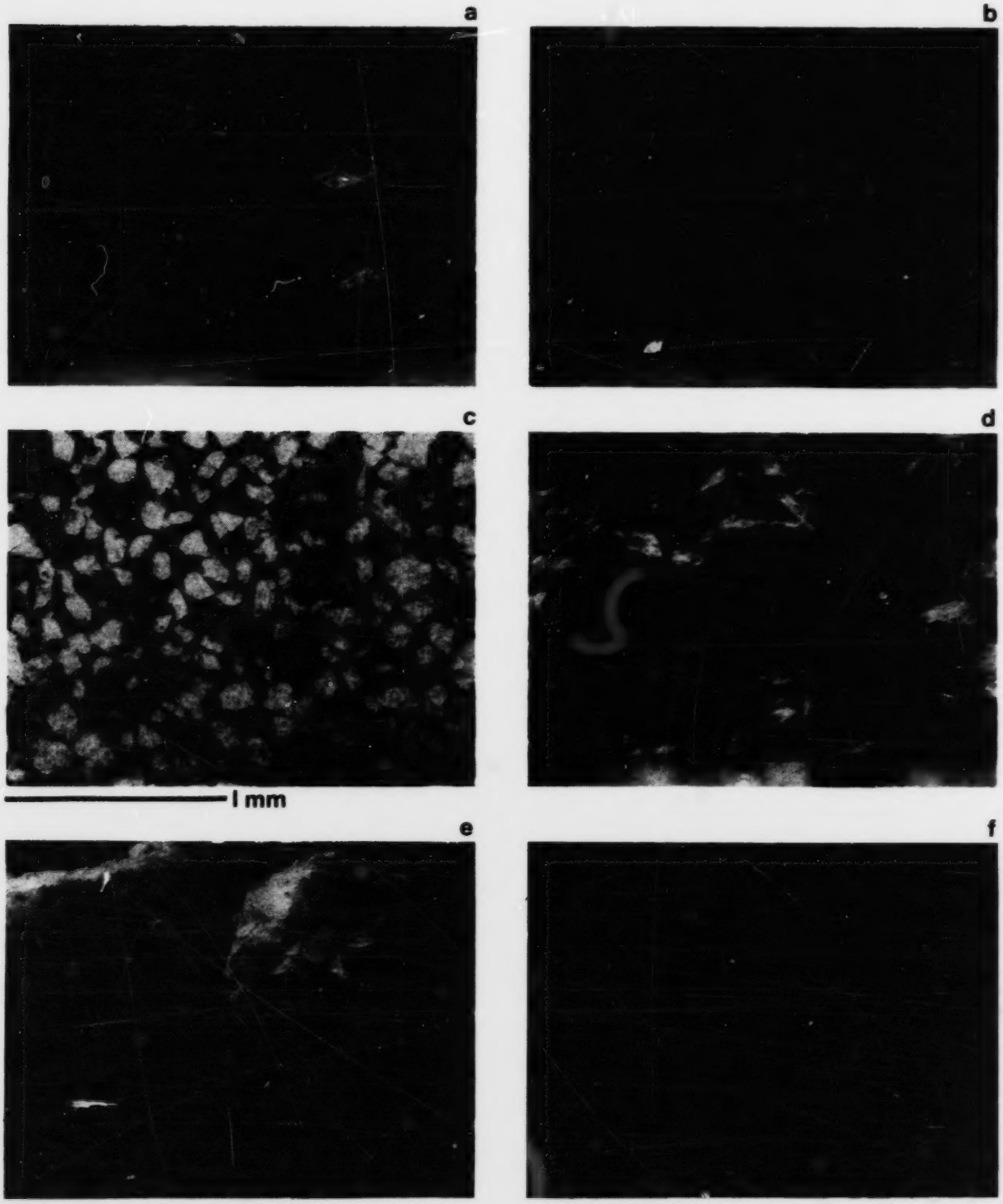


Fig. 2 Thin section and SEM photographs of siliciclastic reservoir sands.
a, b Quartz grains with slightly developed overgrowths, and loosely cemented by scattered dolomite rhombs. B shows closer view of grain with thin oolitic coating (top); to bottom left calcite drusy cement developed over another grain shows later scattered dolomite rhombs (12-12-4-20, see Fig. 5).
c Subrounded to subangular well sorted fine sand and scattered allochem (dark grains). Intergranular porosity is only occluded by scattered development of syntaxial overgrowths to echinoderm fragments (arrowed). (1-22-7-20, see Fig. 9).
d, e SEM views of sands shown in c showing lack of any cement; e shows development of overgrowth on quartz grains with the particle on the right having well developed straight crystal facies.
f Well developed overgrowth on quartz-sand grain, with later dolomite crystals (1-22-7-20, see Fig. 9).

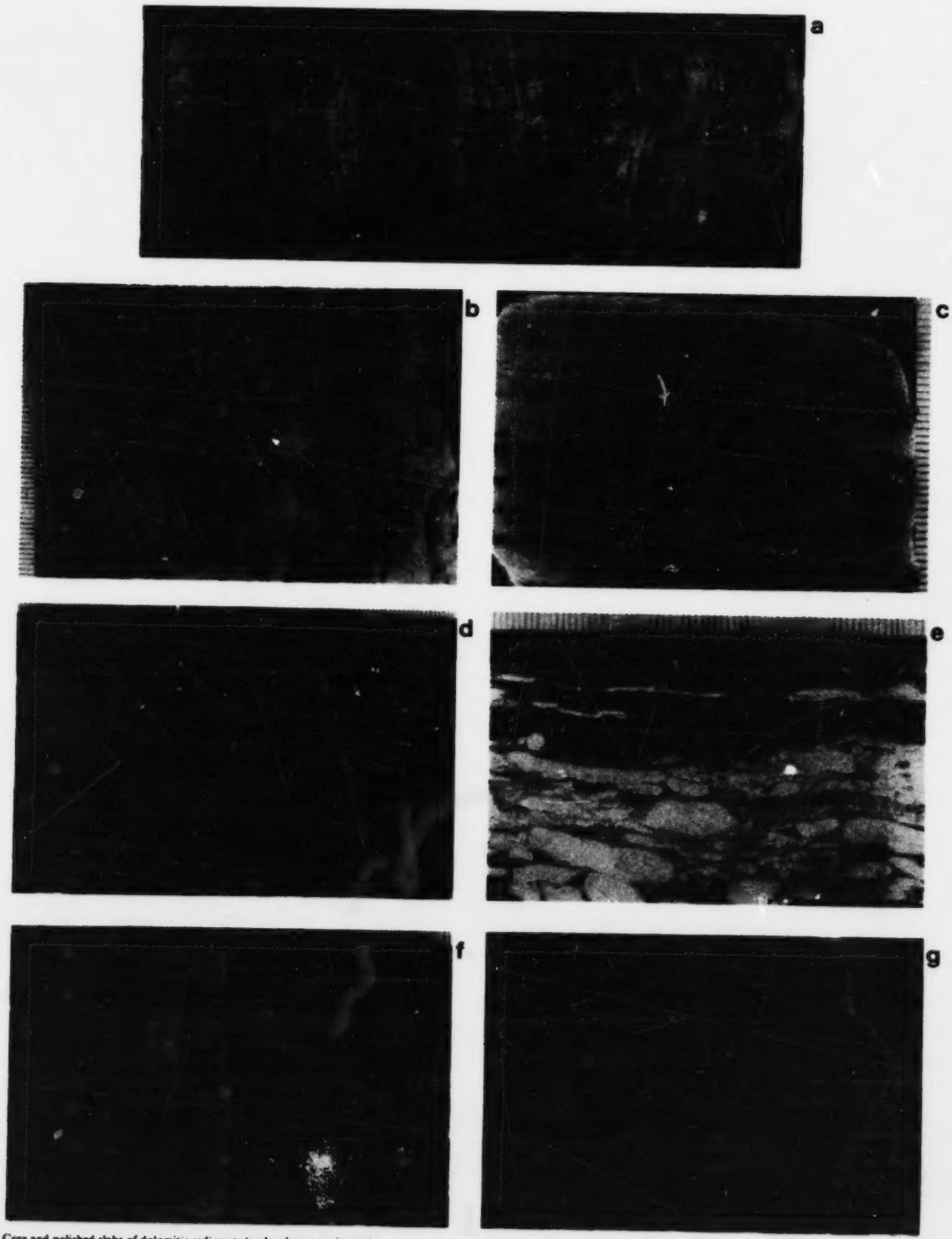


Fig. 3 Core and polished slabs of dolomitic sediments (scales shown are in mm).
a Finely laminated dolomite mud (light) and fine sand (dark); the laminae develop crenulations in parts of the core. (3-16-4-21 see Fig. 7).
b Mottled dolomitic sand (light) and dolomite poor sand, probably caused by burrowing; although the structure is similar to that caused by wind ripples developed in coastal sabkhas (1-18-4-20 see Fig.7).
c Interlaminated dolomitic mudstones and sandstones.
d Interlaminated dolomitic mudstones and sandstones.
e Conglomerate of dolomitic mud clasts set in matrix of oil impregnated sand (1-23-8-25).
f Laminated and brecciated dolomitic mudstone; the brecciated interval contains some vuggy porosity. The specimen is patchily impregnated with oil (1-23-8-25).
g Breccia, possibly produced by dissolution of evaporite minerals, overlying irregularly laminated dolomitic sands and mudstones. Width of sample is 4.5 cm (8-9-10-15).

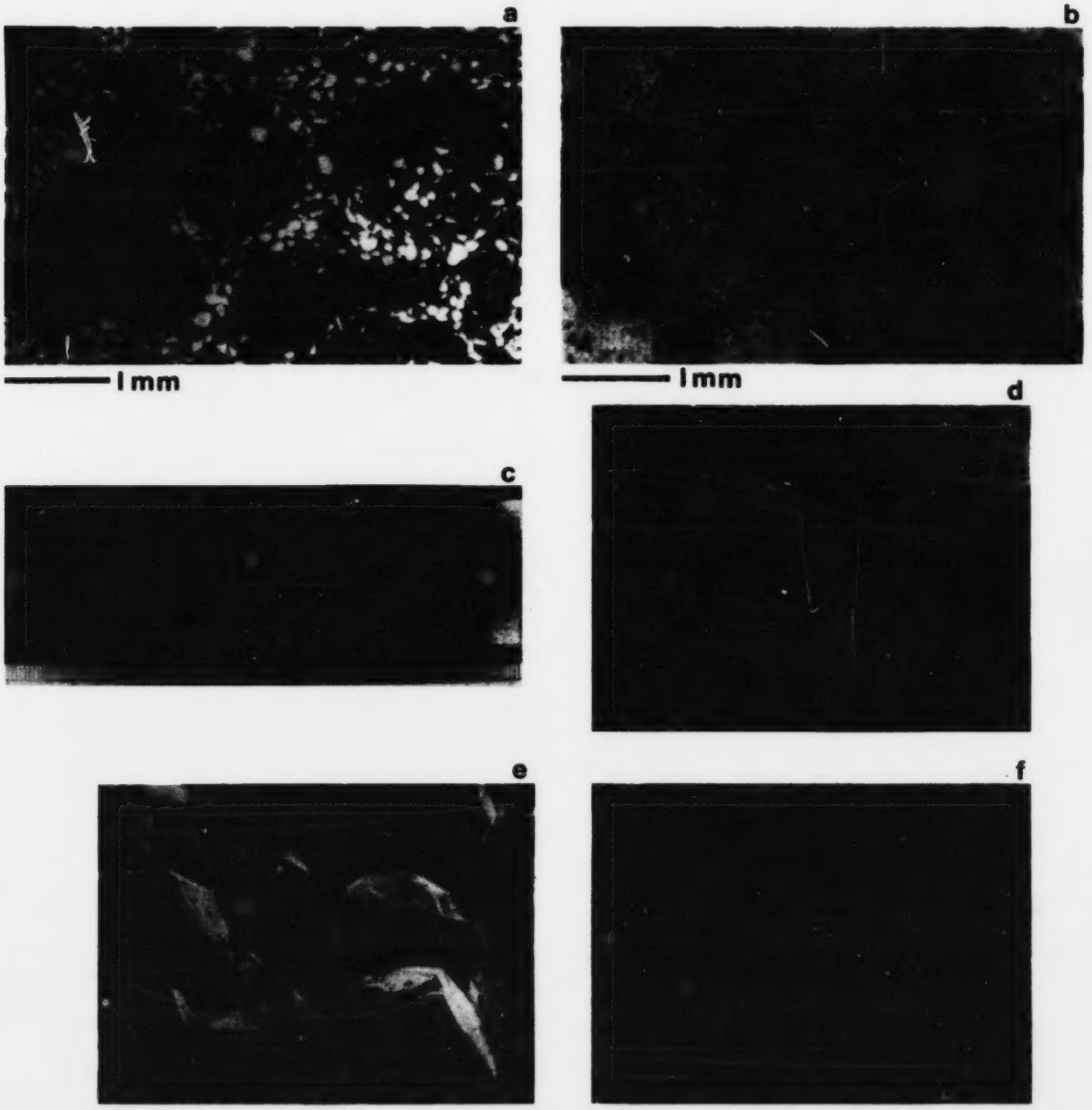


Fig. 4 Polished specimen, thin section and SEM photographs of dolomitic sediments.
a Fine quartz sand grains in a matrix of dolomitic mud; large dark areas are irregular clasts of dolomitic mud that is finer grained than that in the matrix. (1-18-4-20, see Fig. 7).
b Fine quartz sand, with some intergranular porosity (P) partially included by large dolomite rhombs; elsewhere matrix is fine grained dolomite. (12-26-8-29).
c Polished specimen of cross stratified sands alternating with dolomitic muds; top half of specimen is oil impregnated. (1-23-8-25).
d SEM photo of oil-free sand at base of specimen shown in c. Quartz grains with overgrowths are loosely cemented by dolomite rhombs which block pore throats.
e SEM photo of sand from oil impregnated part of specimen shown in c. Dolomite cement is absent, but quartz grains show well developed overgrowths.
f SEM photo of tight sand, showing well developed dolomite matrix and some remaining intragranular porosity(1-22-7-20, see Fig. 9).

LIMESTONES

Peloidal packstones: consist of well sorted fine sand (0.1 - 0.2 mm) grade peloids with some superficial ooids, the amount of quartz sand is variable, sometimes as high as 20 percent (Fig. 5). Skeletal debris may also occur, and is generally much abraded and micritised; in cores this lithology usually shows wavy bedding.

Ooid packstones and grainstones: the grain size of this category ranges from 0.2 to 0.5 mm. Sorting is usually good, but packstones show a greater variability of allochem size. Ooid nuclei consist of quartz grains, peloids or skeletal fragments. Skeletal debris is commonly present. Grainstones are cemented by early (pre-compaction) iron-free drusy calcite fringes with late iron-free equant calcite filling the remaining pores after compaction (Fig. 5, C-E). Dolomite fringes may occur instead of calcite drusy fringes in some grainstones, particularly in the Rapdan area (Fig. 5F). Packstones commonly possess a dolomite mudstone matrix. Sedimentary structures within Upper Shaunavon oolitic rocks are generally indistinct, although high angle (up to 20°) "master bedding" is quite common.

Skeletal sands: the Upper Shaunavon contains a textural spectrum of skeletal sands akin to that illustrated by Folk (1962). Significant amounts of quartz grains of fine sand grade are always present in the skeletal sands. It is clear that skeletal debris forms a significant proportion of Upper Shaunavon limestones. However, intact fossils appear to be relatively rare in the Shaunavon, except where tests of burrowing bivalves are preserved as molds in wavy bedded siliciclastic and carbonate lithologies. The skeletal sands appear to be dominated by molluscan debris; echinoderm plates form a small but significant fraction of the sediments. Some limestones are completely dominated by shells which in life were secreted as calcite; this may be due to sorting or ecological effects, or due to the diagenetic destruction of shells which in life were composed or aragonite. However, diagenetic processes cannot account for sands dominated by skeletal debris that was originally composed of aragonite. Skeletal sands form important reservoirs in the Upper Shaunavon, with submature and mature types exhibiting the best porosity. It is perhaps surprising that supermature skeletal sands do not form good reservoirs, given that they would have possessed good depositional porosities. However, both their depositional intra-particle porosities, and moldic porosities consequent on aragonite solution are today invariably filled with sparry calcite.

LIMESTONE DIAGENESIS

The diagenetic history of the Upper Shaunavon carbonates appears to have been relatively simple. The following general diagenetic sequence can be recognised in the majority of the carbonate sands:

1. dissolution of aragonite shell material;
2. precipitation of iron-free drusy calcite as linings to intra-particle pores, and to shell molds;
3. compaction: fracturing of grains and inter-particle solution;
4. precipitation of calcite spar (usually iron-free) in remaining porosity;
5. continued compaction may occur enhancing earlier grain contact effects, and through the development of stylolites.

Good reservoir units have, it seems, only suffered the first three stages listed above (see Fig. 6).

In the Rapdan Field, some oolite grainstones show dolomite crystals lining inter-particle pores instead of Stage 2 drusy calcite. Ferroan calcite is not commonly developed, and appears rarely in reservoir sands. It is, however, common as moldic fills in large shells present in skeletal wackestones. Occasional vuggy porosity occurs in some mature skeletal sands as a result of both calcite solution and the incomplete cement infilling to shell molds.

The presence of thin layers of shell debris within siliciclastic reservoir sands may result in a severe reduction of their gross vertical permeability, as carbonate cements develop within such layers. Echinoderm plates are particularly important in this regard, as they act as "seeds" for the relatively rapid development of syntaxial overgrowths which quickly plugged pore spaces.

SOME DEPOSITIONAL AND DIAGENETIC ENVIRONMENTAL INDICATORS

No single sediment type can provide unequivocal evidence on which to base environmental interpretations, but a consideration of the nature of the sediments and accompanying diagenetic features present in the Upper Shaunavon helps narrow down the choice of alternative depositional models.

FAUNA AND FLORA

The microfauna (Wall, 1960) and macro-fauna (Christopher, 1964; Paterson, 1968) indicate that the Upper Shaunavon is largely marine in origin. The abundance of echinoderm debris in some sands observed during this study suggests normal marine salinities, but other sediments containing an abundance of one or two bivalve species may indicate raised or lowered salinities. Wall (1960) described charophytes from the Upper Shaunavon, and Paterson (1968) reported a charophyte marker bank about 10 feet from the top of the member. Although charophytes can tolerate saline conditions, today they flourish only in freshwater. The freshwater influence on the deposition of the Upper Shaunavon was also indicated by the ostracod assemblages studied by Brooke and Braun (1972).

WELL SORTED OOLITIC, SKELETAL AND SILICICLASTIC SANDS

The supermature texture of some of the skeletal sands suggests prolonged transport and abrasion in high energy environments, as does the quartz dominant composition of the siliciclastics.

DOLOMITIC SEDIMENTS

Both Christopher (1964) and McMillan (1966) interpreted these sediments as having been deposited in arid tidal flat environments. However, during the present study, few features characteristic of Recent tidal flat sediments, such as those known from Andros Island or the Persian Gulf, have been found. Algal mats and stromatolites (apart from one stromatolitic dolomite noted in 5-14-4-21) are absent, as are features characteristic of exposure such as fenestrae. A few examples of dessication cracks have been found together with brecciated dolomitic mudstone (see Fig. 3F). One example of possible evaporite solution breccias was discovered (Fig. 3G), and this is consistent with the author's discovery of gypsum in the Suction Creek dome section (described by Hearn et al, 1964) Upper Shaunavon equivalent in Montana. Thus there is some evidence to support an evaporative tidal or wind flat origin for the dolomitic sediments.

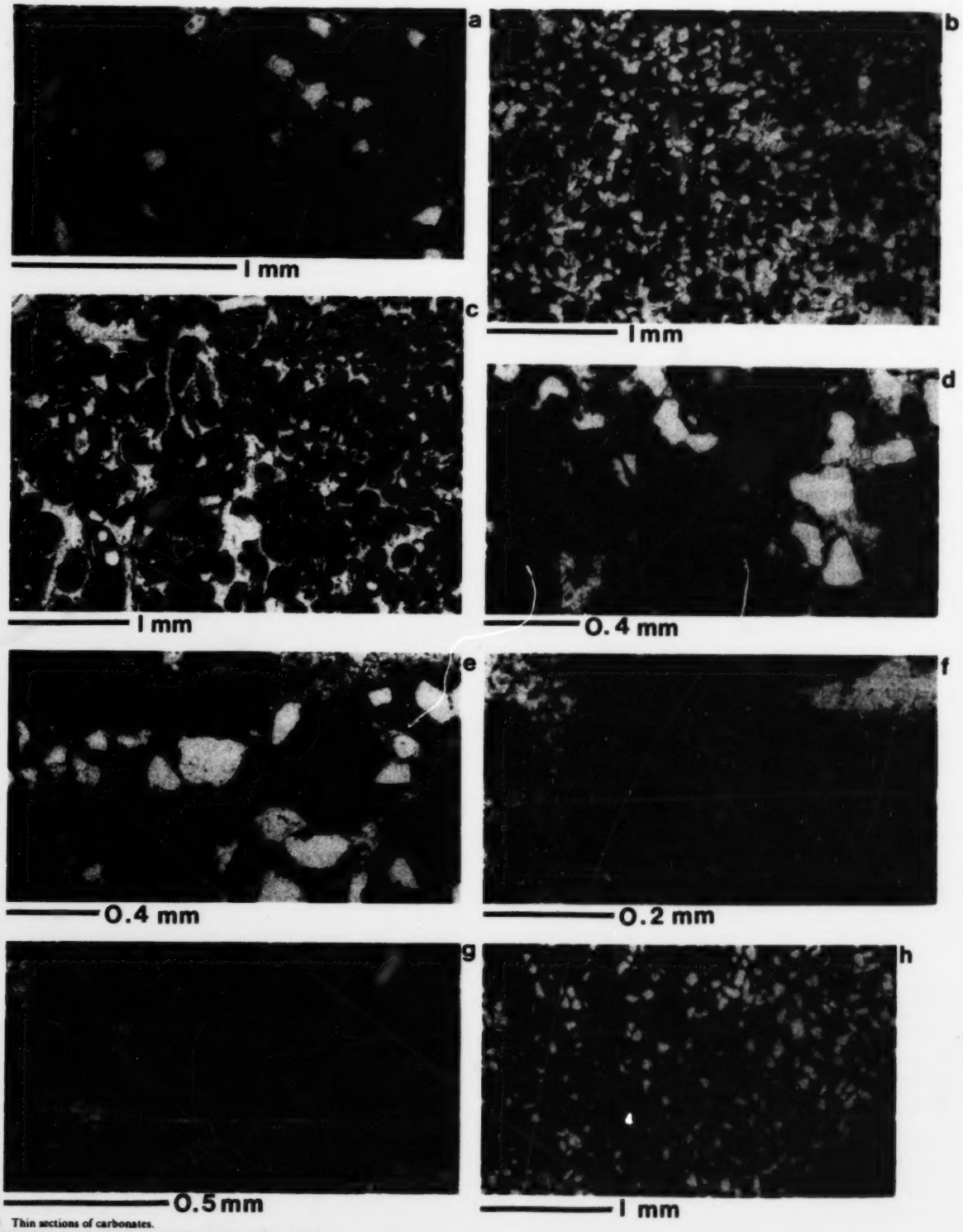


Fig. 5 Thin sections of carbonates.
a Peloid packstone with subsidiary quartz grains (8-16-4-20, see Fig. 7).
b Quartz rich ooid grainstone, with numerous peloid; ooids show thin oolitic envelopes (i.e. superficial ooids). (5-18-4-19, 4655').
c Ooid grainstone showing compaction features; allochems are fringed by drusy calcite cement which formed before intergrain solution between grains. Note also collapse of skeletal mold (arrowed) (5-18-4-19, 4647').
d Ooid grainstone, with drusy calcite fringe formed before intergrain solution (5-14-4-21, see Fig. 7).
e Ooid grainstone, with similar features to that shown in d; note how quartz grains are pressed into allochems due to grain dissolution during compaction (5-14-4-21, see Fig. 7).
f Ooid grainstone with dolomite drusy fringe pre-dating intergrain dissolution; some porosity remains (P). (14-34-3-20, see Fig. 8).
g Dolomitized grainstone/packstone in which the allochems appear to have suffered little dolomite replacement. (8-3-10-20, see Fig. 11).
h Quartz rich dolomitic packstone in which the allochems are partially dissolved to leave pin-point porosity (12-12-4-20, see Fig.8).

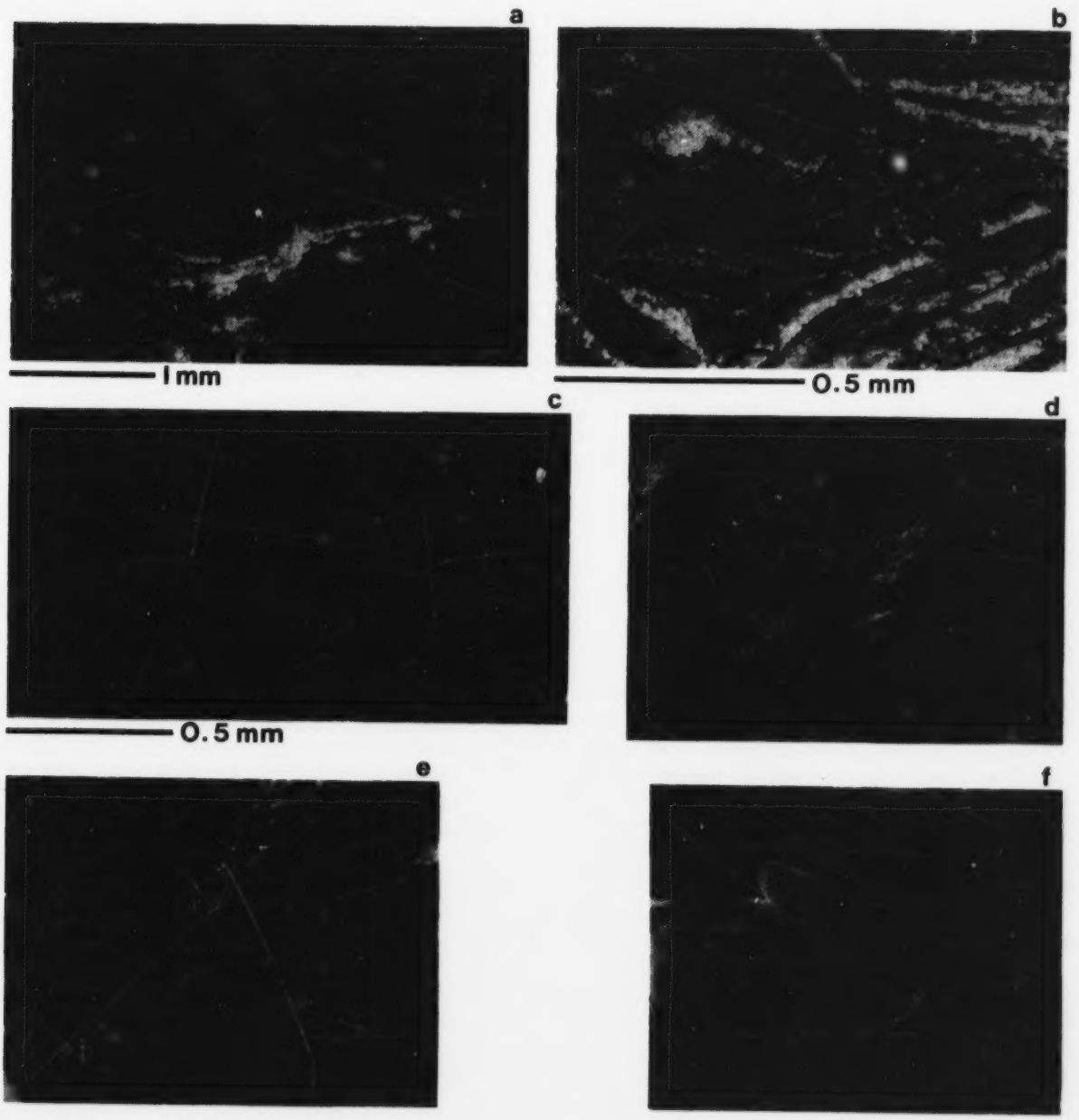


Fig. 6 Thin section and SEM photographs of porous skeletal sands from well 1-22-7-20 (see Fig. 9), Dollard Field.
a, b Skeletal grainstone, with calcite (in life) tests (C), and mass of collapsed micritic envelopes (M). All the allochems are coated by a drusy calcite fringe that cemented the rock prior to compaction of the micritic envelopes and fracture of the large allochem at the top of the photograph.
c Micrite envelope to skeletal grain, with interior showing algal boring preserved by micrite and projecting into moldic porosity. The rock is cemenid by drusy calcite fringe which has not developed inside skeletal grain preserving borings.
d, e, f SEM photographs of shell fragment preserved by micrite envelope and inter- and intra-particle porosity lined by drusy calcite fringe. Note the large pore spaces between this skeletal fragment and other grains.

However, other origins for the dolomite must be considered, the two most plausible of which are detrital (wind-blown) origin, or replacement of calcium carbonate after burial. No unequivocal evidence for detrital dolomite has been found, although one SEM view shows slightly rounded dolomite rhombs. In addition, some structures in dolomitic sands could have been produced by adhesion ripples (see Fig. 3A, B, C). Evidence for dolomite replacement is present, both in the form of replacement fabrics and indirectly in the form of allochems being preserved as empty molds within fine grained dolomites (Fig. 5H). However, fine grained dolomite also occurs as the matrix to ooid packstones, the allochems of which show no dolomite replacement. Some grainstones showing partial dolomite cements also exhibit small patches of fine grained dolomite, suggesting that dolomite cements may have developed as a fine grained fabric. Examples of early, pre-compaction dolomite cement lining pores also occur. To sum up, there is evidence in the Upper Shaunavon favouring three plausible modes of origin of dolomitic sediments:

- tidal flat dolomites, perhaps a mixture of evaporative and detrital dolomite;
- replacive dolomite, possibly produced by the mixing of marine and freshwater (see later discussion on diagenesis);
- dolomite cements, certainly as pore linings, and possibly as fine grained dolomite.

ARAGONITE SOLUTION AND CALCITE CEMENTATION

Upper Shaunavon skeletal sands invariably show aragonite solution followed by the development of drusy fringe calcite cement within both the primary inter-particle and secondary moldic pore spaces. These features are characteristic of the freshwater phreatic diagenetic environment (Longman, 1980) implying a significant flow of freshwater soon after deposition (because the drusy calcite pre-dates any compaction features).

Therefore it is probable that freshwater lenses developed in association with the Shaunavon reservoir sand bodies, which implies emergence. Other evidence for emergence is provided by red shales and apparently random slickensiding in shales probably caused by pedogenic processes. The abundance of charophytes at the top of the Upper Shaunavon also suggests the presence of freshwater.

If freshwater lenses did develop, then mixing zone dolomitization might account for the origin of the dolomitic sediments, which perhaps not coincidentally, occur beneath, or on the flanks of reservoir sands. In this context, it is interesting to note that Christopher (1964, Fig. 11) shows that dolomitization of the Lower Shaunavon occurs to the west of the oil field trend, and lies beneath it in the Instow - Leon Lake area.

No evidence was found to indicate the development of marine cements that are characteristic of beach zones.

CONCLUSIONS

It is clear that the facies assemblages present in the Upper Shaunavon indicate a mosaic of depositional environments, including shallow marine, tidal flats, freshwater, and periods of emergence in which porous sands were subjected to freshwater diagenesis. The extent to which our knowledge of facies sequences and sediment geometries within the Upper Shaunavon can add precision to these interpretations is discussed in the next section.

SAND BODY GEOMETRY AND FACIES SEQUENCES

INTRODUCTION

The NNE-SSW trend along which the Upper Shaunavon reservoir sands are concentrated has already been commented upon. The oil fields, which are usually elongate, are 1 - 2 km wide, and up to 20 km long. From evidence cited earlier, it is clear that their shape is the result of depositional processes being overprinted by diagenetic effects. Clearly, the location of freshwater lenses which appeared to have been so important in both producing porosity (through aragonite solution) and occluding it (through calcite cementation) would have been controlled significantly by the geometry of units originally possessing high primary porosities. Thus the shape of the oil fields may offer some clues concerning the broad depositional environment of the Upper Shaunavon.

Shallow marine and barrier system sand bodies exhibit the following general characteristics (see reviews by Elliot, 1986; Johnson and Baldwin, 1986; Reinson, 1984; Walker, 1984).

Barrier Islands: the Barrier systems are oriented parallel to the shore, but inlet fills (which have the highest preservation potential) may be oriented perpendicular or oblique to this trend; they possess erosive contacts with underlying sediments. Barriers fringing microtidal seas are long and narrow, whereas those bordering mesotidal seas are short and stunted (Moslow and Tye, 1984). Microtidal barriers are considerably affected by storms causing frequent washovers, whereas mesotidal barriers exhibit washover and tidal deltas. Tidal inlet migration, driven by longshore currents in wave dominated environments, are likely to dominate microtidal barrier systems (Moslow and Tye, 1984).

Shallow marine storm sand ridges: may be up to 10 m high, 2 -3 m wide and a few tens of kilometres long; they are commonly oblique to the shoreline.

Shallow marine tidal sand ridges: may be shore parallel or oblique, and those on the edge of the continental shelves (e.g. in the Celtic Sea) may be normal to the shelf edge. They are up to 40 m high, up to 5 km long, and range in length from 15 to 90 km. Extensively cross-bedded sandstone bodies probably have a tidal origin, whereas a broader range of structures indicates a storm origin.

The dimensions of the larger oil field areas and their orientation with respect to the inferred palaeoslope preclude a microtidal barrier system dominated by tidal inlet migration driven by longshore currents. If they originated as a mesotidal barrier system, then evidence for tidal inlets and associated tidal deltas should be present, together with some of the characteristic features of shoreface, foreshore and backshore sands, with lagoonal sediments situated behind (to the west) of them. If the Shaunavon reservoir sands were deposited as tidal sand ridges, they should largely be encased in marine sediments, and oriented either parallel to the shoreline, or perpendicular or oblique to a shelf break of some kind.

The characteristic features of sequences in the three oilfield areas studies are reviewed in the next section in the light of the previous discussion. Summary sections of cored intervals are depicted on Fig. 7 - 11. Although previous reports describing the Shaunavon have used fence diagrams, this practice is not adopted here, for the well spacing on the figures is seldom less than a kilometre, and usually much more. Given the dimensions of modern barrier sands and shallow marine sand ridges, only the well spacing achieved in producing areas is likely to reveal

the true nature of the geometry of the Shaunavon reservoir sands.

Both Christopher (1964) and McMillan (1966) divided the Upper Shaunavon into three units. McMillan's division was quite simple; a lower blue gray limestone "bundle" (oolitic, peloidal and coquinoidal limestones and gray calcareous shales), a middle sand "bundle" (including dolomitic sediments), and an upper lithologically more heterogeneous interval. Christopher's division was as follows:

U3: sandy coquinoidal channel fills of the Dollard and Instow-Bone Creek oilfields; variable lithologies elsewhere;

U2d: algal nodule bed, grading into sandstones with bright gray and green laminations;

U2c: tan sandstone and dolomite, grading into oolites in the south;

U2b: green dolomitic and calcareous mudstone and shale, grading westward into dolomites;

U2a: blue-gray limestone;

U1: very fine grained sandstone and bioclastic limestone (the most variable of the three units).

Christopher suggests that Unit 1 is capped by a disconformity, but cites no palaeontological evidence to support its presence. His use of these units to construct fence diagrams correlating successions over wide areas is open to doubt, as apart from the algal nodule horizon (which appears in about half the wells studied by McMillan, 1966), there appear to the present author to be no reliable marker horizons present.

THE LOWER PART OF THE UPPER SHAUNAVON

McMillan's lower bundle probably is roughly equivalent to Christopher's Units U1 and U2. In the Rapdan and Dollard areas (see Figures 7 - 10) it consists of calcareous shales, sandy skeletal packstones and grainstones (the latter often supermature), peloidal grainstones,and sand-shale mixtures. The skeletal packstones are similar to the coquinoid sands described by Brenner and Davie (1973, 1974) from the Oxfordian of Montana, Wyoming and South Dakota, and interpreted as storm lag deposits. The skeletal grains in some limestones are very well rounded, yet set in a fine matrix of carbonate mud and fine quartz sand, suggesting rapid dumping of sediment, possibly as washover deposits. In contrast well sorted grainstones may have been winnowed over prolonged periods of time by storm or tide generated current activity. In the Dollard area, wavy bedded and bioturbated fine sand and silts show low angle bedding that was possibly caused by lateral accretion of tidal channels. Low angle bedding in skeletal sands is also seen in this area. In the wells studies in the Instow - Bone Creek area, the lower part of the Upper Shaunavon is developed mostly as skeletal and ooid grainstones, some of which form producing reservoirs.

On the evidence available, it is impossible to propose an environmental interpretation of the lower part of the Upper Shaunavon with any confidence. The most plausible interpretation is that it represents largely reworked relict sediments of a barrier system that transgressed across the region studied.

THE MIDDLE AND UPPER PARTS OF THE UPPER SHAUNAVON IN THE RAPDAN AREA

The middle part of the Upper Shaunavon in this area contains dolomitic mudstones, quartz rich dolomitic mudstones, and quartz and ooid sands. As commented earlier, the ooid sands contain early dolomite cement, and some packstones have a dolomitic matrix. At some intervals, the carbonate grains are only present as empty vugs in a dolomite matrix. The porosity of the sands seems largely to be inversely proportional to the amount of dolomite cement or matrix present.

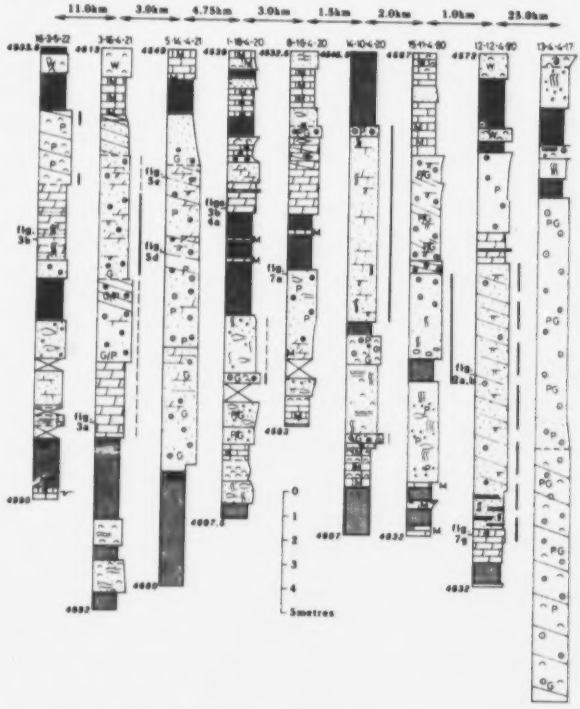


Fig.7 Sketch logs of cores from the Rapdan Oilfield and nearby areas (for location of boreholes, see Fig. 1). For key, see Fig. 8.

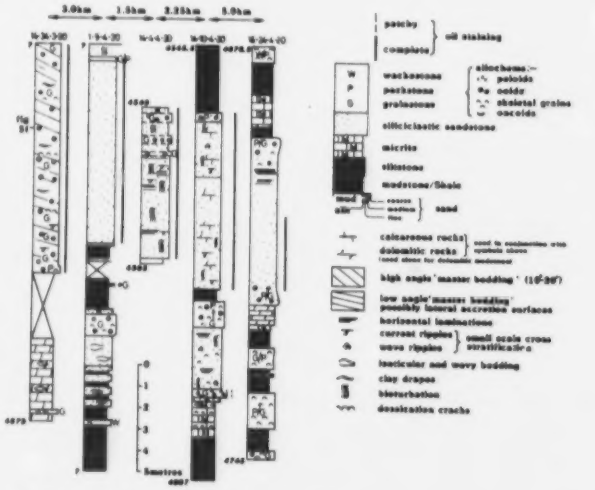


Fig. 8 Sketch logs of cores from the Rapdan Oilfield and nearby areas (for location of boreholes, see Fig. 1) and key to Figs. 7 - 11. The symbols below are used to depict the broad features of Upper Shaunavon cores studies. The successions are hung arbitrarily on the base of the Vanguard Formation. The logs were completed from original measurements of the cores, with the only allowance for missing core being made when gaps were left in the core boxes (unfortunately no percentage recovery is given on the core boxes). This has resulted in the thicknesses of the successions depicted not corresponding to the true thicknesses. As the main purpose of this work was a rapid reconnaissance study,it was decided not to waste time trying to adjust the logs to give true thicknesses. Depths of tops and bases of logs are shown in feet unless stated otherwise.

The quartz and ooid sands often overlie dolomitic sediments, but in places they are absent and only the dolomites are present. In one case, dolomites occur within the sands (12-12-4-20). These relationships could be interpreted in terms of the sands forming in tidal inlets and deltas associated with a barrier system containing extensive wind flats or supratidal zones in which dolomites formed. Alternatively, the sands might have formed as tidal sand ridges after transgression had occurred across an extensive tidal/wind flat area in which the dolomitic sediments were deposited as a regressive cap to the underlying lower part of the Upper Shaunavon. This would imply that the later top Upper Shaunavon sediments, and also the Vanguard Formation, must have draped the sand-ridge topography.

Whatever the origin of the Rapdan sands, they appear to be distinct from those of the oil fields to the north. They contain more ooids, are cemented by dolomite, and the trend of the individual oilfields in the area is generally NNE-SSE in contrast to the NW-SE trend of the Dollard and Instow - Bone Creek fields. This contrast in orientation suggests that the Rapdan ooid sands may be tidal sand ridges developed parallel to the barrier system in which the fields to the north formed. Another possibility is that the sand bodies formed during transgression of an earlier barrier inlet system similar to that described by Swift et al (1972) from the eastern U.S.A. shelf. To the east of the Rapdan area there appears to be a belt of oolitic sediments that trends approximately at right angles to the oilfield trend. This pattern is similar to that described by Swift et al (1972) which they interpret to result from coastal retreat during transgression, which leaves a shelf transverse sand body reworked by storm generated currents. The sediments overlying the sands (micrites, shales and bioturbated sands) could either represent lagoonal sediments formed behind a barrier system, or between sand ridges consequent on a sea level fall.

THE MIDDLE AND UPPER PARTS OF THE UPPER SHAUNAVON IN THE DOLLARD AREA

In the wells studied, dolomitic sediments are less in evidence than they are in the Rapdan area; they do not occur beneath the reservoir sands, but become important in sequences to the east and west (see Fig. 9).

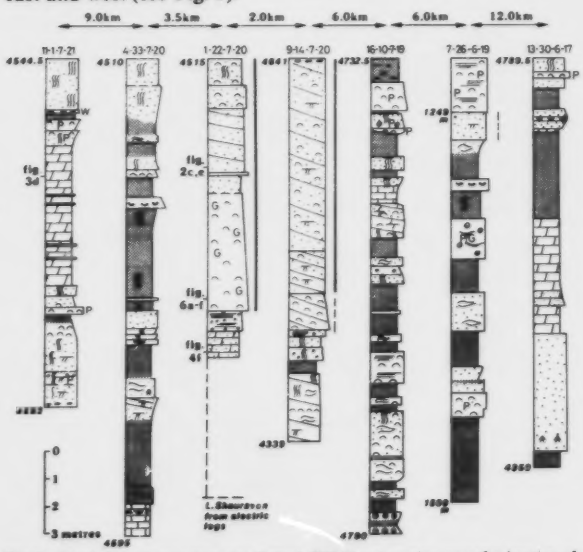


Fig. 9 Sketch logs of cores from the Dollard Oilfield and nearby areas (for location of boreholes, see Fig. 1, and for key see Fig. 8).

Christopher shows an isopachous map for his U3 unit in the Dollard area (1964, Fig. 26) which, from a review of data in his core descriptions (1966) appears to approximate the thickness of skeletal and quartz sand in the field. The thickness distribution has a marked asymmetry, with very rapid thinning SW (to less than 3 m) of the NW-SE axis of a maximum thickness of 20 m, but gradual thickening to the NE. The axis of maximum thickness coincides with a narrow zone along which the sands rest on the Lower Shaunavon (see Christopher, 1964, Fig. 25). This suggests that the sand unit has an erosive base, in which case it probably formed as a tidal channel. An alternative possibility is that the sand geometry was caused by a tidal sand body, for its size and asymmetry are appropriate for such an origin. However, such a sand body would have to have been initiated at the beginning of the Upper Shaunavon transgression, as it rests on the Lower Shaunavon in places. To the north, the sand interval is situated above the pisolite horizon (see Fig. 10, 15-19-7-19). In the absence of sufficient slabbed cores, it is impossible to determine the extent to which the Dollard sand is in fact a composite body.

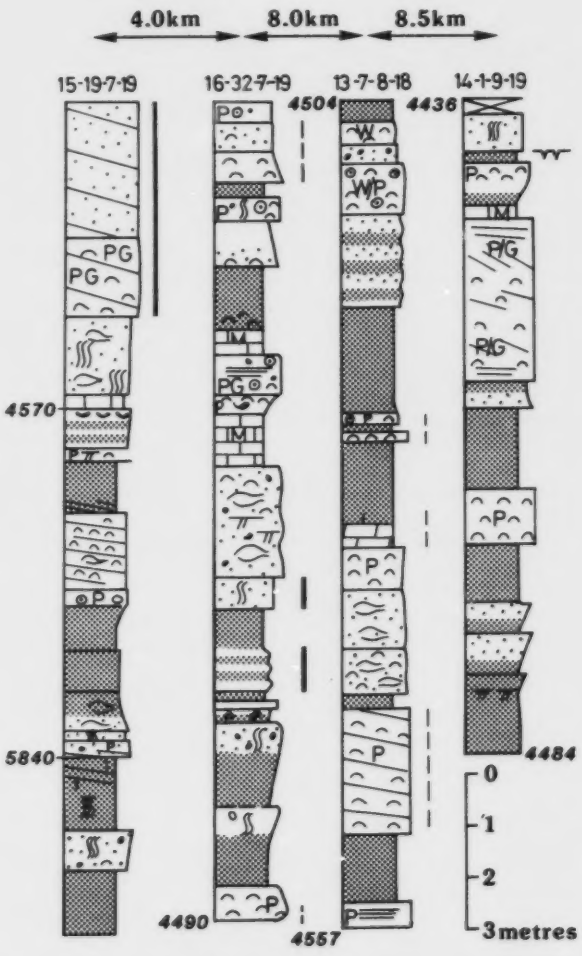


Fig. 10 Sketch logs of cores from the Dollard Oilfield and areas to the north of it (for locations of boreholes, see Fig. 1, and for key, see Fig. 8).

THE MIDDLE AND UPPER PARTS OF THE SHAUNAVON IN THE INSTOW - BONE CREEK AREA

Some of the cross-bedded reservoir sands in the Bone Creek field occur above the pisolite horizon (Fig. 11, wells 2-34-10-19, 10-24-10-19), and to the west (14-19-10-19) and northwest (4-14-11-20) sands overlying this horizon are extensively bioturbated — not a feature characteristic of a flood delta sequence which might be expected in these locations if the Instow - Bone Creek field developed as a tidal channel. In the wells further to the SE, along the axis of the field, the reservoir sands are thicker (3-13-10-19, 9-7-10-18) and the pisolite is absent. To the southeast of the field, well 5-10-9-17 penetrated thick well cemented skeletal sands beneath the pisolite. Thus it is possible that the reservoir interval comprises stacked sand bodies, and that it does not have an erosive contact with underlying sediments. Dolomite sediments appear beneath the pisolite on both sides of the oil field trend.

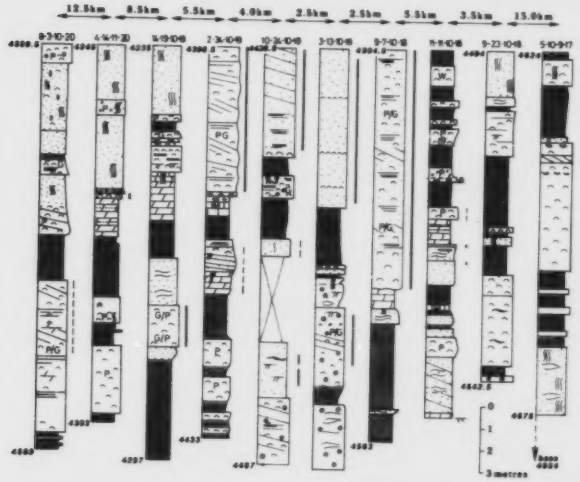


Fig. 11 Sketch logs of cores from the Instow - Bone Creek oilfield and nearby areas (for location of boreholes, see Fig. 1, and for key, see Fig. 8).

CONCLUSIONS

The Upper Shaunavon reservoirs are marine sands that suffered later emergence during which freshwater phreatic diagenesis occurred. The Rapdan sands are more ooid rich than those to the north, and are apparently situated at the eastern end of a belt of thick, but non-porous ooid sands that extend to the southeast, suggesting the formation of ooid shoals, possibly during a transgression which caused coastal retreat to the west.

The dolomitic sediments formed either as tidal or wind flat sediments, with the dolomite having an evaporative origin, or deposited as wind blown detritus from Upper Paleozoic outcrops around the Williston Basin, or as mixing zone diagenetic dolomite replacing micrites and micritic sandstones. A tidal channel origin for the Dollard and Instow - Bone Creek sands seems probable, but no clear evidence for tidal deltas has been found. It is possible that they formed during a relative sea-level stillstand after the transgression during which the Rapdan sands were deposited, or possibly during a slight regressive episode when the coast began to advance eastwards due to sediment progradation.

If dip-meter data were available it would enable a much clearer interpretation of Upper Shaunavon depositional environments to be made. However, in its absence, more precision might be possible if a careful study was made of cross stratification types present in the reservoir sands; this would require many of the cores to be slabbed.

The industry view of the Upper Shaunavon oil field trend being a barrier system separating dominantly marine shales to the east from fluviatile/blanket sands to the west is clearly oversimplified. Reddened shales occur to the east of the oilfield trend in several wells (see Christopher 1964, McMillan 1966, and well 6-16-1-16 examined by the present author). In the few wells studied west of the trend, dolomitic sands are common but skeletal debris is also present, suggesting that transgressive episodes may have spread far to the west, temporarily inundating coastal flat environments.

ACKNOWLEDGEMENTS

This work was funded by the Geological Survey of Canada. I am grateful to Jack McMillan for suggesting this study, and for his help in facilitating my visit to Canada in 1984. My work also benefited from discussions with Terry Poulton and Kirk Osadetz, (Institute of Sedimentary and Petroleum Geology, Calgary), Jim Christopher (Saskatchewan Energy and Mines) and Paul Godkin (Saskoil). The willing assistance of Doug Paterson and his staff at the Subsurface Geological Laboratory is gratefully acknowledged. I thank Don Kent (University of Regina) for his help in providing Tritthart's (1980) undergraduate thesis, and for allowing me to use his department's photomicroscope. Canterra Energy Ltd. are thanked for allowing access to McMillan's (1966) report on the Upper Shaunavon. Colin Dunn and Geoff Parslow provided professional help and hospitality during my stays in Regina.

I thank colleagues at the Open University for their assistance and patience (Beryl West: word processing; Dick Carlton: SEM; Ian Chaplin: thin sections; John Taylor: plates; Jane Turner: SEM and section staining).

REFERENCES

Bridges, P.H. 1982, Ancient offshore tidal deposits. In: A.H. Stride (ed.), Offshore tidal sands, Chapman & Hall, London, p. 172-192.

Brooke, M.E. & Braun, W.K., 1972. Biostratigraphy and Microfauna of The Jurassic System of Saskatchewan, Sask. Dept. Mineral Resources Rept. 161, 83 p.

Christopher, J.E. 1964. The Middle Jurassic Shaunavon Formation of south-western Saskatchewan. Sask. Dept. Mineral Resources, Rept. 95, 95 p.

Christopher, J.E. 1966. The Middle Jurassic Shaunavon Formation of south-western Saskatchewan, Lithologic descriptions of selected cored sections. Sask. Dept. Mineral Resources, Rept. 110, 308 p.

Elliott, T. 1986. Siliciclastic shorelines. In: Reading, H.G. (ed), Sedimentary environments and facies (2nd ed.), Blackwell Scientific Publications, Oxford, p. 43-177.

Folk, R.L. 1972. Spectral subdivision of limestone types. In: W.E. Ham (ed.), Classification of carbonate rocks. Am. Assoc. Petrol. Geol. Mem. 1, p. 62-84.

Hearn, B.C., Pecora, W.T., & W.C. Swadley, 1964. Geology of th Rattlesnake Quadrangle, Bearpaw Mountains, Blaine County, Montana. U.S. Geol. Surv. Bull., 1181-B.

Johnson. H.D. & Baldwin, C.T. Shallow siliciclastic seas. In: Reading, H.G. (ed.), Sedimentary environments and facies (2nd ed.), Blackwell Scientific Publications, Oxford, p. 207-258.

Longman, M.W. 1980. Carbonate diagenetic textures from near surface diagenetic environments. Am. Assoc. Petrol. Geol. Bull. 64, p. 461-487.

McMillan, N.J. 1966. Sedimentation of the Upper Member of the Shaunavon Formation (south-west Saskatchewan). Internal report, Tenneco Oil and Minerals Ltd.

Moslow, T.F. 1984. Depositional models of shelf and shoreline sandstones. Am. Assoc. Petrol. Geol. Cont. Ed. Course Notes Series 27, 102 p.

Moslow, T.F. & Tye, R.S. 1985. Recognition and characterization of Holocene tidal inlet sequences. Marine Geology. 63, p. 129-151.

Paterson, D.F. 1968. Jurassic megafossils of Saskatchewan with a note on Charophytes. Sask. Dept. Mineral Resources, Rept. 120, 135 p.

Poulton, T.P. 1984. The Jurassic of the Canadian Western Interior, from 49°N latitude to Beaufort Sea. In: D.F. Stott & D.J. Glass (eds.). The Mesozoic of Middle North America. Can. Soc. Petrol. Geol. Mem. 9. p. 15-41.

Reineck, H.E. & Singh, I.B. 1973. Depositional Sedimentary Environments. Springer-Verfag, New York, 439 p.

Reinson, G.E. 1984. Barrier Island and associated strand plain systems. In: Walker, R.G. (ed.) Facies Models (2nd ed.), Geoscience Canada, Reprint Ser. 1., p. 119-140.

Swift, D.J.P., Kofoed, J.W., Saulsbury, F.P. & Sears, P. 1972. Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America. In: Swift, D.J.P., D.B. & O.H. Pilkey (eds.), Shelf Sediment transport: process and pattern, Dowden Hutchison & Ross, Stroudsburg, p. 499-574.

Tritthardt, A.D., 1980. The lithologies and depositional environment of The Upper member of the Shaunavon Formation of the Whitemud Field. University of Regina BSc. Thesis.

Walker, R.G. 1984b. Shelf and shallow marine sands. In: Walker, R.G. (ed.) 1984a Facies Models (2nd ed.). Geoscience Canada Reprint Series 1. 14170.

Wall, J.H. 1960. Jurassic microfaunas from Saskatchewan. Sask. Dept. Mineral Resources, Rept. 53, 299 p.

STRUCTURAL EVOLUTION OF THE CENTRAL AND SOUTHERN PORTIONS OF THE NESSON ANTICLINE, NORTH DAKOTA

JULIE A. LEFEVER[1], RICHARD D. LEFEVER[2] AND SIDNEY B. ANDERSON[1]

[1]North Dakota Geological Survey
University Station
Grand Forks, N.D. 58202

[2]Department of Geology
University of North Dakota
Grand Forks, N.D. 58202

ABSTRACT

The Nesson Anticline is the largest producing structural feature in the North Dakota portion of the Williston Basin. It extends for approximately 110 miles (175 km) along a north-south line from just south of the Canadian border to the Killdeer Mountains. All of the Paleozoic formations which occur in the Williston Basin are present along at least part of the anticline and, of these, 14 produce in a total of 54 fields.

Data were collected from oil well wireline logs along the portion of the anticline from Beaver Lodge Field to its southernmost extension in Rattlesnake Point Field. A total of 45 formation tops were picked from about 1300 well logs. From these data, isopach maps and structure contour maps were constructed for each of the formations. Where there were enough control points away from the structure, structural relief was determined.

The Nesson Anticline in the study area is predominantly a north-south trending structure with slight irregularities in direction along the hinge trace. The fold opens up to the south, where it splits into several smaller secondary folds. Two faults are apparent from the structure maps: the main western Nesson fault which extends the length of the structure, and a fault on the northeast side of the Antelope Anticline.

There are nine recognizable areas on the Nesson Anticline in the study area. Structural activity in each area seems to have been essentially independent of the other areas. In most of the areas, the greatest movement along the anticline occurred during Devonian or Early Mississippian time, although there are some exceptions. Significant movement may have occurred prior to deposition of the Ashern Formation, but the available data are too few to allow that interpretation. Structural activity in most areas appears to have been episodic, with few instances of prolonged movement.

INTRODUCTION

The Nesson Anticline is the largest producing structural feature in the North Dakota portion of the Williston Basin. Approximately 110 miles (175 km) long, it is highlighted by nearly continuous production along a north-south line from just south of the Canadian border (T163N) to the Killdeer Mountains (T146N; Fig 1). All of the Paleozoic formations which occur in the Williston Basin are present along at least part of the anticline and, of these, 14 produce in a total of 54 fields (Fig.2). The success ratio and the presence of possible multiple pay zones has made the anticline a continued target for oil field development and exploration.

This paper deals with the majority of the Nesson Anticline, from Beaver Lodge Field (T156N) to its southernmost extension in Rattlesnake Point Field (T1456N). The purpose of this paper is to document the development of this structural feature through the Paleozoic and most of the Mesozoic.

Fig. 1 Index map of Williston Basin, showing location of study area.

PREVIOUS WORK ON THE NESSON ANTICLINE

The Nesson Anticline was originally identified by a U.S. Geological Survey field party mapping lignite beds in the Ray quadrangle in 1917. In 1918, A. J. Collier of the U.S. Geological Survey continued the mapping of the anticline using an alidade and plane table. In the resulting paper, Collier formally named the anticline the "Nesson". He also stated

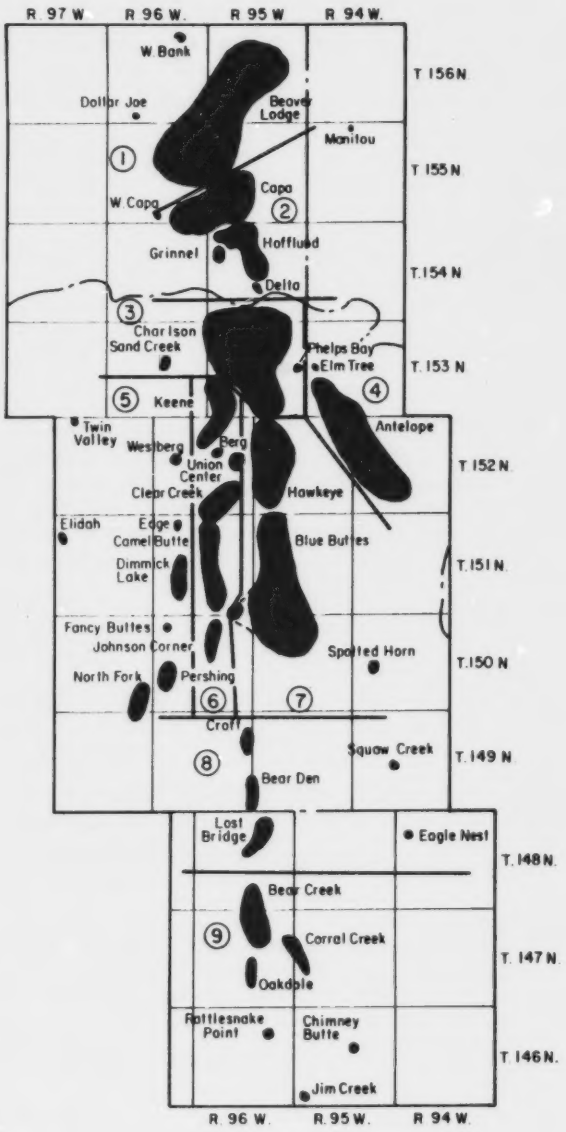


Fig. 2 Principal fields developed on the central and southern part of the Nesson Anticline. Outlined and numbered areas are the individual areas referred to in text.

that, in his opinion, the chances of finding oil in the Nesson were small (Collier, 1919, p. 216). Dove (1922) did additional work north of the Missouri River to augment Collier's preliminary study.

Beginning about 1937, a large amount of oil and gas leasing occurred in western North Dakota and, as a result, several reconnaissance surveys and one seismographic survey were done (Nevin, 1946). The seismographic work done by Amerada Petroleum Corporation of 1946 resulted in the discovery of the Beaver Lodge Field in 1951 (Laird et al, 1955).

Actual drilling on the Nesson Anticline started in 1935 with drilling by the Big Viking Oil Company in SWNE Sec. 3, T145N, R96W. This well reached a depth of 4642 feet, and yielded some gas, although not in commercial quantities. In 1938, the California Company drilled the #1 Kamp well (NWNE Sec. 3, T154N, R96W). This well reached a depth of 10,287 feet and might have been commercial if it had not been abandoned due to a stuck drill pipe (Laird et al, 1956).

The major discovery, however, occurred on April 4, 1951 by Amerada Petroleum Corporation, in what is now Beaver Lodge Field. This well, the #1 Clarence Iverson, was tested in several intervals before oil was recovered from the Silurian. Originally completed in the Silurian (perforated interval from 11,630-11,660; flowed 307 barrels of oil and 25 barrels of water), it was deepened to 11,955 feet and then plugged back to the Devonian (perforated interval 10,490-10,530; initial production of 290 barrels of oil). In September 1951, while drilling the #1 H. O. Bakken, Amerada Petroleum reported a flow of oil from the Madison on a drill stem test. Following this recovery, the #1 Palmer Dilland well in the Beaver Lodge Field recovered oil on a drill stem test in the Madison. As a result of these two recoveries, Amerada Petroleum recompleted the #1 Clarence Iverson in the Madison (perforated interval 8,520-8,528; initial production of 667 barrels/day) in December 1951. This was the first Madison completion in the state. Amerada then completed the #1 Bakken in the Mission Canyon from 8,312 to 8,350 feet on April 14, 1952 (Laird et al, 1956). This was the discovery well for Tioga Field. Over the next five years, five new fields were discovered and by 1956 Beaver Lodge and Tioga Madison pools were almost completely developed (Laird et al, 1956).

Since the initial discovery in 1951, 54 fields have been discovered, making the Nesson Anticline the most productive feature in the state.

METHODS

Data were collected from all available oil well wireline logs along this portion of the anticline. This includes the wells in the area encompassed by T146N - T145N, and R94W - R97W. The data are primarily from wells along the Nesson Anticline, but also include those in R94W and R97W as additional control points.

The depths to the top of all the identifiable formations were recorded from each of the logs. A total of 45 formation tops were picked from about 1300 well logs (Table 1). These are the primary data on which this study is based. From these data, isopach maps were constructed for each of the formations (Table 2), and structure contour maps drawn for each horizon. The control below the top of the Interlake Formation is limited, and that below the top of the Red River Formation extremely limited.

Where the data permitted, smaller portions of the anticlines were considered in more detail. These areas are those in which there has been extensive drilling activity and thus correspond in a general way to the major producing fields (Table 3). By so doing, it was hoped to determine whether different parts of the structure behaved similarily through time, or whether differences exist. We did not regard these areas as discrete structural elements (although some appear to be), but were simply treating the areas of high well density as convenient divisions. Eight areas were originally delineated, and one was added after inspection of the results revealed significant differences with the area of which it was a part. The areas will be referred to in the remainder of this paper by the numbers given in Table 3.

Table 1. Formation tops used in this study.

Formation	No. of Picks	Formation	No. of picks
Greenhorn	1252	Lodgepole	474
Mowry	1320	Bakken	479
Inyan Kara	1319	Three Forks	477
Jurassic	1320	Birdbear	439
Rierdon	1329	Duperow	439
Spearfish Fm		Souris River	350
Saude Mbr	1316	Dawson Bay	319
Pine Salt	1293	Prairie	318
Belfield Mbr	1297	Winnipegosis	309
Minnekahta	1206	Ashern	317
Opeche	1318	Interlake	318
Minnelusa	1321	Stonewall	140
Tyler	1329	Stony Mountain	140
Otter	1328	Red River	140
Kibbey		Red River-Winnipeg	
Kibbey Sandstone	1330	Transition	21
Kibbey Limestone	1330	Winnipeg Gp	
Kibbey Shale	1331	Roughlock Fm	21
Madison	1331	Icebox Fm.	21
Charles	1332	Black Island Fm	21
Mission Canyon	1341	Deadwood	16
		Precambrian	3

Table 2. Formation isopachs used in this study.

Formation	No. of points	Formation	No. of points
Greenhorn	1252	Bakken	477
Mowry	1316	Three Forks	439
Inyan Kara	1316	Birdbear	439
Spearfish Fm		Duperow	350
Saude Mbr	1288	Souris River	319
Pine Salt	1296	Dawson Bay	318
Belfield Mbr.	1179	Prairie	309
Minnekahta	1310	Winnipegosis	317
Opeche	1311	Ashern	317
Minnelusa	1327	Interlake	139
Tyler	1327	Stonewall	140
Otter	1329	Stony Mountain	140
Kibbey		Red River	21
Kibbey Sandstone	1329	Red River-Winnipeg	
Kibbey Limestone	1331	Transition	21
Kibbey Shale	1329	Winnipeg Gp	
Charles	1323	Roughlock Fm	21
Mission Canyon	474	Icebox Fm	21
Lodgepole	476	Black Island Fm	16
		Deadwood	3

Table 3. Discrete areas on the Nesson Anticline and principal producing fields in each.

Area	Principal Fields
1	Beaver Lodge
2	Capa, Hofflund
3	Charlson
4	Antelope
5	Camel Butte, Edge
6	Keene, Clear Creek, Johnson Corner
7	Hawkeye, Blue Buttes
8	Croff, Bear Den, Lost Bridge
9	Bear Creek, Oakdale, Corral Creek, Rattlesnake Point

Formation thicknesses were examined in each of the areas, and formations which thinned noticeably across the structure were noted. Where control permitted, structural relief, the difference in elevation between the structure and the control points away from the structure, was determined for each area. To ensure that only structural movement was being recorded, only conformable formation tops were used and, for comparative purposes, only those wells which penetrated all of the conformable units down to the Ashern Formation (19 units in all) were used (a total of 238 wells). Due to a paucity of data, no tops below the Ashern Formation could be used for relief determination.

RESULTS AND INTERPRETATION

Structure contour maps were made of the Nesson Anticline in the study area for 23 different formations or marker beds. These maps reflect essentially the present form and features of the fold. Data are limited for the deeper formations (Table 1), so the resulting maps are limited in detail (see Fig. 3).

The Nesson Anticline is predominantly a south-plunging fold. From its northern margin to approximately where the Missouri River crosses the structure, it is closed with the hinge surface inclined slightly to the west. South of the Missouri River the fold becomes more open and maintains an upright position.

The hinge trace was mapped for all of the structure maps generated. Formations deeper than the Devonian Souris River lack the data control to precisely define the positions of the hinge line. Although the fold follows an overall north-south direction, the hinge line bends slightly along the trace of the fold. The most notable change in direction occurs just south of the Beaver Lodge Field. Consistently on each of the maps there is a change in direction of the hinge line at this point from a northeasterly orientation to a northwesterly one. The next notable change occurs at the Charlson Field, where the fold splits into three folds: 1) oriented to the southeast and named the Antelope Anticline; 2) the main and best developed branch of the Nesson Anticline which continues south through Hawkeye and Blue Buttes Fields; and 3) a secondary fold that is not as well developed as the main fold in line with Clear Creek and Camel Butte Fields. In addition to these smaller folds, the maps indicate that there may be an additional fold parallel to the Antelope Anticline to the southeast of Blue Buttes Field (in line with Squaw Creek and Eagles Nest Fields). The hinge line of the main part of the Nesson can be traced as far as Oakdale Field in the southernmost portion of the study area.

Two other notable inferred features from the structure maps are two faults that occur along the structure. On the western side of the Nesson Anticline, from the northern part of the study area (Beaver Lodge field) to just south of T15ON, is the western Nesson fault. Active since the Precambrian, the western Nesson fault has moved intermittently through time; the dominant direction of movement is the west side down (Gerhard et al, 1982). The second fault occurs along the northeast side of the Antelope Anticline. It is evident only on structure contour maps of the Devonian-Mississippian Bakken Formation and younger units; this restriction may be due to lack of control for the deeper horizons in that area. Direction of movement is northeast side down.

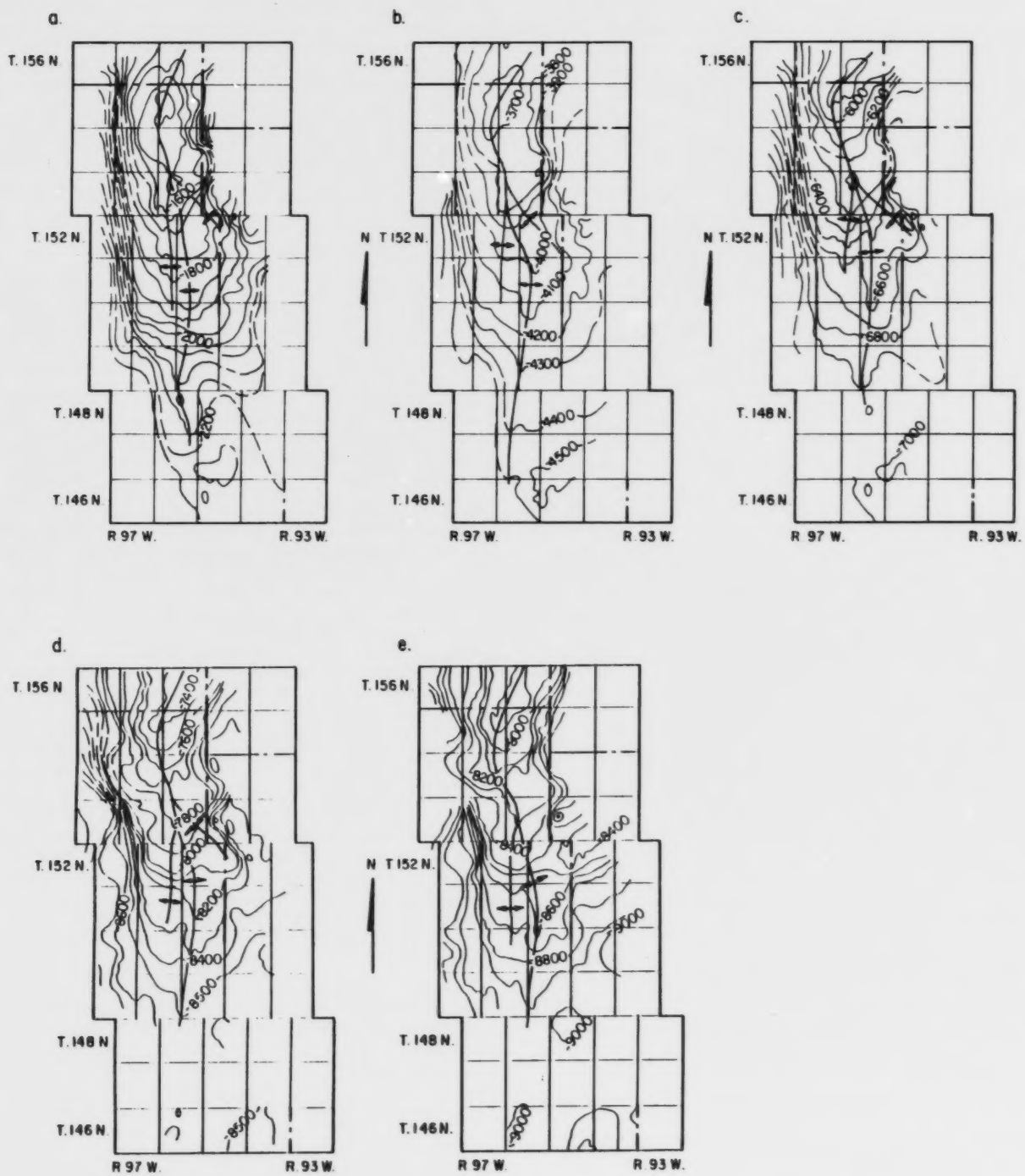


Fig. 3 Structure contour maps on selected horizons in the study area; a) Top of Greenhorn Formation (contour interval =50 ft), b) Top of Spearfish Formation (contour interval = 100 ft), c) Top of Mission Canyon Formation (contour interval = 100 ft), d) Top of Bakken Formation (contour interval = 100 ft), e) Top of Duperow Formation (contour interval = 100 ft).

HISTORY OF MOVEMENT ALONG THE STRUCTURE

Isopach maps of all the principal units were constructed; representative maps of different parts of the column are shown in Figure 4.

The structural relief plots (Fig. 5) illustrate the difference in elevation between the highest and lowest points on a given horizon across the structure in each of the areas. The relief on a given unit is a function of the net tectonic activity since deposition of the unit, so continued uplift in an area should produce an increase in relief with increasing age (e.g., upper curve in Fig. 5b), while continued subsidence should produce the opposite trend (e.g., lower curve in Fig. 5b). The numbers given below for amount of uplift and relief in specific areas are taken from the relief plots; they are included only to convey some idea of the relative amounts of movement. Factors other than tectonic activity, such as local topographic relief or compaction, may also affect the structural relief, so these diagrams should be regarded as qualitatively correct in showing direction and magnitude of tectonic movement, but not as precise indicators of tectonic uplift or subsidence, especially on a small scale.

The discussion of events which follows is based on our interpretation of the isopach maps and of the relief plots. For convenience of discussion, and because in some instances the divisions seem to correspond to genuine differences in tectonic history, we have chosen to discuss each of the areas defined above as a separate entity. The relative ages of the units were taken from Ballard et al (1983); the corresponding absolute ages used below are from Harland et al (1981).

Area 1

Movement on the structure in Area 1 was relatively minor through most of Devonian time, with the exception of some minor movement in the southernmost part of the area during deposition of the Duperow Formation, as indicated on the isopach map. The earliest major movement in the area is recorded during the interval from Mission Canyon through Kibbey time. Significant thinning of the formations is evident, especially in the southern part of the area, and relief of about 100 feet was produced (Fig. 5a). This was followed by a short period of quiescence or relative subsidence from 325-305 Ma; evidence for this is the greater thickness (20-40 ft more than the surrounding area) of the Otter Formation along structure, and the indication of about 40 feet of subsidence on the relief plot.

From the deposition of the Tyler Formation to the deposition of the Inyan Kara Formation (305 - 120 Ma), relative upward movement on the structure seems to have occurred at an approximately constant rate. Virtually all of the isopach maps for that interval show areas of noticeable, but not major, decreased thickness along the axis of the structure, and the structural relief trend is essentially a straight line.

During the Inyan Kara - Greenhorn interval (120-89 Ma), there seems to have been little uniform movement on the structure, although local thick and thin areas are present.

During the interval following Greenhorn deposition, a minimum of 200 feet of relief was produced in Area 1, resulting in the present structure. The history of this last phase of movement is unknown, as no data for this study were collected above the Greenhorn.

Area 2

Area 2 has sufficient control, and is of a suitable shape, to make it feasible to discuss the northern and southern parts of the area individually. This practice will be followed with several of the areas.

The northern part of Area 2 generally seems to have had much less activity than the southern part. During Devonian and Mississippian time, except for the Bakken - Lodgepole interval (359 - 352 Ma), when there seems to have been minor uplift of about 40 feet, there was either noticeable subsidence (a total of at least 90 feet in the Devonian) or minor subsidence or quiescence (Mississippian) (Fig. 5b). Sometime during deposition of the Tyler Formation (ending about 305 Ma), relative uplift began, and continued at least through deposition of the Spearfish Formation (245 Ma). For example, the isopach maps of the Tyler and Spearfish Formations indicate a definite thinning in the northern part of Area 2. The relief plot shows approximately 100 feet of relief produced during this time. From Spearfish to Inyan Kara deposition (245 - 118 Ma), there was evidently very little uplift (less than 10 feet on the relief plot). Some renewal of uplift (about 50 ft) occurred during the Inyan Kara - Greenhorn interval (118 - 89 Ma); the Inyan Kara and Greenhorn isopach patterns show thinning in the northern part of Area 2. Some 180 feet of relief was added in this part of Area 2 in post-Greenhorn time.

The southern part of Area 2, by contrast, was the most active of any so far examined along the Nesson Anticline. During the Devonian and Mississippian, a total of about 425 feet of relief was generated. Most of the uplift (about 360 feet) evidently occurred during the Devonian; the relief plot of the formations from the Ashern through Bakken Formations (381 - 359 Ma) shows a steeply decreasing line, and the isopach maps for most of the Devonian units show at least some thinning in the northern part of Area 2 (e.g., Duperow Formation, Fig. 4e).

The rate of relative uplift seems to have abruptly decreased after deposition of the Bakken Formation (359 Ma); the slope of the relief plot is much less than for the older units, although about 60 feet of relief was produced. Thickness differences across the structure are not as evident for the Mississippian units; the Mission Canyon Formation (Fig. 4d) is an exception. Uplift seems to have continued, although apparently at a declining rate, until sometime after Tyler Formation deposition (305 Ma), when it evidently reached a very low rate, as indicated by the essentially flat relief plot. Ispoach maps of the units in that interval show small thickness differences across the southern part of Area 2 (e.g., Mowry-Skull Creek isopach, Fig. 4a). An additional relief of nearly 400 feet was developed in this area after Greenhorn deposition.

Area 3

The northern part of Area 3 shows little evidence of relative uplift before Mississippian time. About 60 feet of relief was generated during the interval between deposition of the Bakken and Tyler Formations (359-305 Ma); isopach maps of the formations in that interval show noticeable thinning, as for example, in the Mission Canyon Formation (Fig. 4d), which shows a thickness difference of 40-60 feet across the northern part of Area 3. Following Tyler deposition, this part of Area 3 seems to have undergone some subsidence, as indicated by the relief plot (Fig. 5c) and the lack of thinning on the isopach maps. There seems to have been some minor uplift during the Inyan Kara-Greenhorn interval, as suggested by the Mowry-Skull Creek isopach (Fig. 4a), although the relief plot indicates no significant movement. Post-Greenhorn relief in this part of Area 3 is about 130 feet.

Fig. 4 Isopach maps of selected formations in the study area; a) Mowry-Skull Creek (contour interval = 10 feet), b) Spearfish Formation (contour interval = 20 feet), c) Tyler Formation (contour interval = 25 feet), d) Mission Canyon Formation (contour interval = 25 feet), e) Duperow Formation (contour interval = 10 feet).

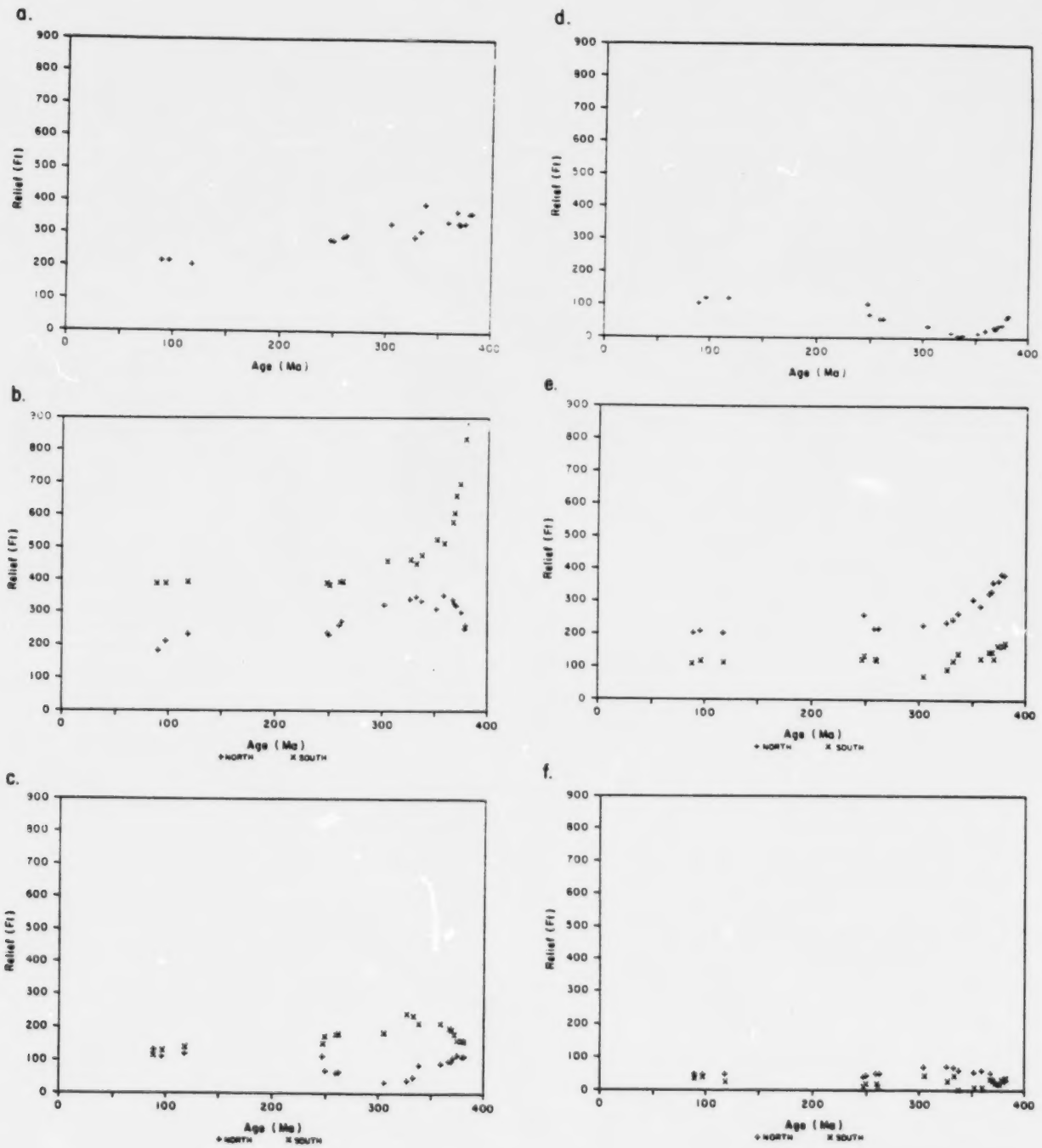


Fig. 5 Diagrams of structural relief (difference between the highest and lowest elevation on a specified horizon) versus age; a) Area 1, b) Area 2, c) Area 3, d) Area 4, e) Area 5, f) Area 6, g) Area 7, h) Area 8, i) Area 9.

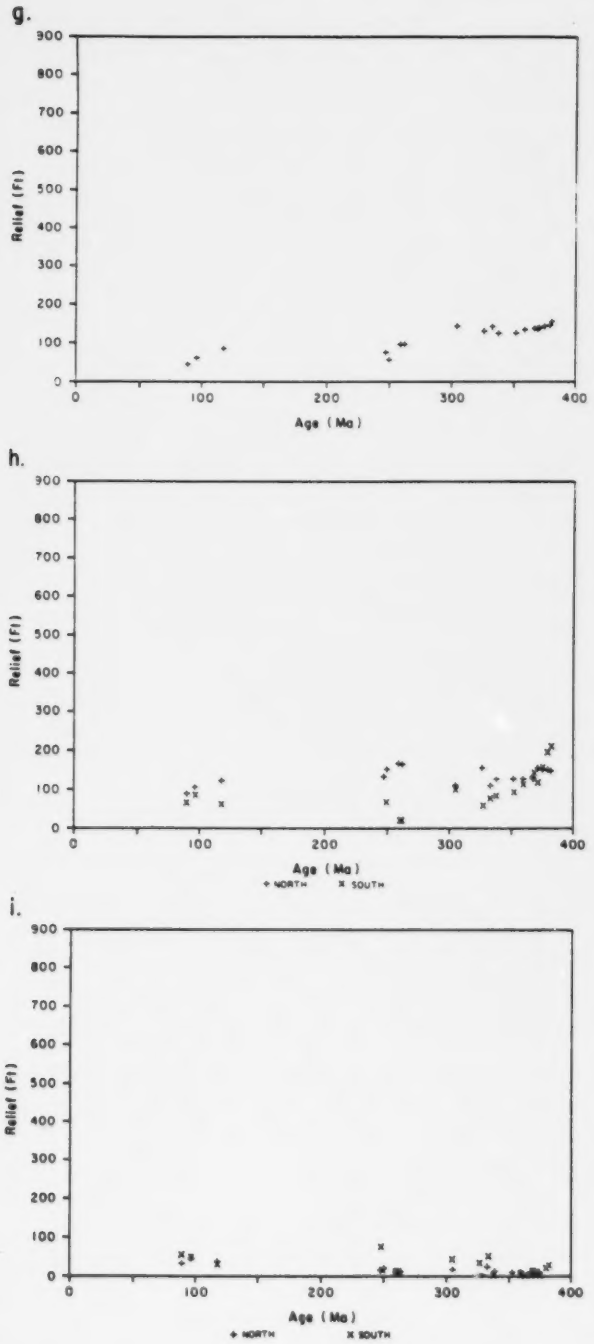


Fig. 5 Diagrams of structural relief (difference between the highest and lowest elevation on a specified horizon) versus age; a) Area 1, b) Area 2, c) Area 3, d) Area 4, e) Area 5, f) Area 6, g) Area 7, h) Area 8, i) Area 9.

The southern part of Area 3 appears to have been subsiding through the Devonian and Mississippian; the relief plot (Fig. 5c) indicates a difference of about 80 feet between the relief on the oldest and youngest units of these ages, and the isopach maps (e.g., Duperow Formation, Fig. 4e) show some thickening across this part of Area 3. Relative uplift appears to have begun during this time between deposition of the Kibbey Formation and the Tyler Formation (327-305 Ma); most of the uplift (about 60 feet) seems to have been during that interval, but uplift seems to have continued throughout the remainder of the time for which we have data (305 - 89 Ma) (e.g., Mowry-Skull Creek isopach, Fig. 4a). About 110 feet of relief was generated in the southern part of Area 3 after Greenhorn deposition.

Area 4

In Area 4, the only significant uplift of the structure (Antelope Anticline) with respect to the area on either side occurred during Devonian and Mississippian time (380 - 333 Ma) during the deposition of the Ashern through Charles Formations, when a total of about 60 feet of relief was generated transverse to structure. Thereafter, the structure seems to have subsided some 110 feet with respect to the surrounding area through deposition of the Spearfish Formation (245 Ma), and to have been quiescent or very slightly uplifted since that time.

The isopachs indicate a lack of thickness variation across the structure, but show some differences along the structure (e.g., Mowry-Skull Creek isopach, Fig. 4a). This probably indicates that the structure in this area ceased to move upward with respect to both sides after Devonian time, and instead was tilted along with the surrounding area on the south. This resulted in a southeast-plunging block, which is reflected in the present structure.

The uplift and development of the Antelope Anticline with respect to the fault on the northeast side could not be documented due to a lack of well control away from the structure to the northeast. There has almost certainly been more structural activity than is indicated by the relatively restricted data set.

Area 5

Area 5 shows evidence of uplift over most of the interval for which data exist, both in its northern and southern parts. In both parts, uplift seems to have persisted through the Devonian and Mississippian, producing about 170 feet of relief in the north and 120 feet in the south. The isopach maps show significant thinning across the area for units deposited during that time (e.g., Duperow Formation, Fig. 4e).

During deposition of the Tyler to Spearfish Formations (305 - 245 Ma), the northern area subsided about 40 feet; most of the movement was during Spearfish time. The southern part of the area underwent subsidence, which produced a relief difference of some 70 feet, largely in the time between Tyler and Spearfish deposition.

In both areas, little evidence exists for movement after Spearfish deposition. The relief plots are essentially flat, and the isopach maps of the younger formations (e.g., Mowry-Skull Creek isopach, Fig. 4a) shows no thinning across the structure.

Approximately 200 feet of relief (north) and 100 feet of relief (south) were generated in Area 5 after deposition of the Greenhorn Formation.

Area 6

The northern part of Area 6 underwent only minor vertical movement until Tyler deposition (305 Ma), when relative uplift began, and continued through deposition of the Spearfish Formation (245 Ma), and produced a total relief for that interval of about 35 feet. The isopach maps for this area, except for the Tyler Formation (Fig. 4c), show no noticeable thinning across the structure.

The history of the southern part of Area 6 is similar, except that there seems to have been some minor uplift during the interval between Birdbear and Bakken deposition.

The isopach maps for Area 6 show little evidence of relative vertical movement in either the northern or southern parts. Instead, the principal variation in thickness is along the structure (e.g., Tyler Formation, Fig. 4c), indicating that the mode of movement was tilting rather than uplift or subsidence with respect to the surrounding area.

Area 7

Area 7 was quiescent or underwent only minor uplift through the Devonian, producing only about 30 feet of relief during the interval from deposition of the Ashern Formation through Lodgepole deposition (381 - 352 Ma); the isopach maps for the formations deposited during that time show only minor thinning across the structure (e.g., Duperow Formation, Fig. 4e).

Beginning in Mission Canyon time, there was significant uplift in the northern part of Area. 7. This is not reflected on the relief plots because none of the control points for relief in Area 7 are in the northern part; consequently, we can only describe times of activity, and not approximate amounts of uplift or relief. From Mission Canyon time onward, most of the formation isopachs show noticeable thickness differences across the northern part of Area 7 (e.g., Mission Canyon Formation, Fig. 4d: Mowry-Skull Creek isopach, Fig. 4a), indicating persistent uplift, at least for the interval between 338 and 89 Ma.

The southern part of Area 7 shows no significant uplift until after deposition of the Tyler Formation (305 Ma). From that time through deposition of the Spearfish Formation (245 Ma), about 90 feet of relief was generated. Some expression of this uplift is evident on the isopach map of the Spearfish Formation (Fig. 4b). Subsequently, there was some subsidence (about 30 feet) between Spearfish and Inyan Kara deposition (245 - 120 Ma), followed by about 40 feet of relative uplift during the Inyan Kara - Greenhorn interval (120 - 89 Ma); the latter event is reflected in the Mowry-Skull Creek isopach map (Fig. 4a). Only 40-50 feet of relief was produced by post-Greenhorn activity in the southern part of Area 7.

Area 8

In the northern part of Area 8, except for minor uplift (about 15 feet) during Mission Canyon time, the area seems to have been inactive or slowly subsiding through most of the Devonian and Mississippian. The relief plot indicates about 65 feet of net subsidence (Fig. 5h); the only isopach map to indicate uplift during that interval is the Duperow Formation (Fig. 4e). Between Kibbey and Tyler deposition, about 45 feet of relief was produced; the effect of uplift is apparent on the Tyler Formation isopach (Fig.4c). Following Tyler deposition, the northern part of Area 8 seems to have subsided by at least 50 feet. From Opeche through Greenhorn deposition, there appears to have been about 70 feet of uplift; roughly equal subsidence took place during the Opeche - Spearfish and the Inyan Kara - Greenhorn intervals. Some expression of the uplift is evident on the Mowry-Skull Creek isopach (Fig. 4a).

The southern part of Area 8 was considerably more active than the northern part over most of the time span for which data exist. Uplift was rapid between Ashern and Souris River deposition (381 - 371 Ma), when about 95 feet of relief was produced. The isopach maps of the formation in that interval reflects this activity, and show significant thinning across the structure. This was followed by minor subsidence (about 25 feet) between Souris River and Duperow time (371 - 369 Ma); some increased thickness of the Duperow Formation is evident on the isopach map (Fig. 4e). From the end of Duperow deposition through Kibbey time, the southern part of Area 8 underwent about 80 feet of uplift, most of the uplift (about 50 feet) occurred during deposition of the Bakken and Lodgepole Formations (359 - 352 Ma), and is reflected in the isopach maps on those formations. From deposition of the Kibbey to the Tyler Formations, the southern part appears to have undergone subsidence; the relief difference between those two units is about 40 feet. Between Tyler and Opeche deposition, there was about 80 feet of uplift. From the end of Opeche deposition until deposition of the Mowry, the southern part underwent a gradual subsidence, producing a relief difference of about 60 feet. During the interval encompassing deposition of the Mowry and Greenhorn Formations, about 25 feet of uplift occurred; some thinning of the Mowry-Skull Creek isopach is apparent on the isopach map (Fig. 4a).

A total of about 90 feet of relief was produced in the north and about 60 feet of relief in the south after Greenhorn deposition.

Area 9

Area 9 has undergone less uplift or subsidence than any of the other areas examined in this study. Moreover, the vertical movements seems to have been less persistent than in other areas.

In the northern part of Area 9, there was a total of about 15 feet of relief produced by uplift during the interval between deposition of the Ashern and Souris River Formations (381 - 371 Ma) (Fig. 5i). From Souris River deposition through most of Mission Canyon deposition, there appears to have been very little activity on the structure. The Mission Canyon Formation isopach is the only one for that interval which shows thinning across the structure in the northern part of Area 9. Beginning probably late in Mission Canyon time, uplift began and continued through deposition of the Kibbey Formation; the relief produced was about 20 feet. From Kibbey time through the end of Greenhorn time, the northern part of Area 9 shows evidence for only minor vertical movement; the isopach maps show only local thickening or thinning (e.g., Mowry-Skull Creek isopach, Fig. 4a), and do not indicate any general movement. Only about 30 feet of relief was produced in the northern part of Area 9 after Greenhorn deposition.

The southern part of Area 9 underwent about 20 feet of uplift between deposition of the Ashern and Souris River Formations; this uplift is not generally reflected in the isopach maps of the formation in that interval. From Duperow time through deposition of the Mission Canyon Formation, there was essentially no relief produced in the southern part of Area 9. Except for some local thick and thin areas (e.g., Duperow Formation, Fig. 4e), the isopach maps for that interval do not show the effects of uplift or subsidence. In the time between Mission Canyon and Charles deposition, the southern part

subsided by some 50 feet. Between deposition of the Charles (333 Ma) and deposition of the Spearfish (245 Ma), the southern part underwent about 40 feet of uplift, most of it before deposition of the Opeche Formation; the isopach map of the Tyler Formation (Fig. 4c) shows thickness differences indicative of this uplift. From the end of Opeche deposition (262 Ma) through deposition of the Spearfish Formation (245 Ma), there appears to have been no activity in this part of Area 9. Following Spearfish deposition, a gradual subsidence began, and continued through Greenhorn time; about 25 feet of relief was produced by this episode.

Approximately 30 feet of relief was produced in the northern part, and 50 feet in the southern part after deposition of the Greenhorn Formation.

SUMMARY

From the preceding discussion, it is evident that the uplift or subsidence events which occurred in each area were essentially independent of other areas. No two areas seem to have very similar histories of tectonic activity. Because of this, it seems likely that each of these areas was behaving as an independent block during the interval represented by the data. It may be that more detailed data would reveal even smaller-scale areas which acted independently, although such data will probably not be available in the near future.

In most of the areas, the greatest uplift along the Nesson Anticline occurred during the Devonian or, in some cases, the Early Mississippian. The only exceptions to that are areas 6 and 7, where the greatest uplift occurred during Pennsylvanian time. Due to a lack of data below the Devonian units, we were unfortunately unable to date precisely the beginning of the Nesson as a positive feature. Significant movement may have occurred prior to deposition of the Ashern Formation (381 Ma), the oldest unit for which we have enough data, but we cannot be certain.

In most of the nine areas, movement, whether uplift or subsidence, seems to have been episodic, with uplift alternating with quiescence or subsidence. There are few examples of prolonged movement, either positive or negative, for the interval for which data exist.

CONCLUSIONS

1) The Nesson Anticline in the study area is predominantly a north-south trending structure with slight irregularities in direction along the hinge trace. The fold opens up to the south, where it splits into several smaller secondary folds.

2) Two faults are apparent from the structure maps: the main western Nesson fault which extends the length of the structure, and a fault on the northeast side of the Antelope Anticline.

3) The Nesson Anticline in the study area includes nine distinct areas. Structural activity in each area seems to have been essentially independent of the other areas.

4) In most of the areas, the greatest movement along the anticline occurred during Devonian or Early Mississippian time, although there are some exceptions. Significant movement may have occurred prior to deposition of the Ashern Formation, but the available data are too few to allow that interpretation.

5) Structural activity in most areas appears to have been episodic, with few instances of prolonged movement.

REFERENCES CITED

Ballard, W. W., Bluemle, J. P., and Gerhard, L. C., (coordinators), 1983, Correlation of stratigraphic units of North America - Northern Rockies/ Williston Basin correlation chart: American Association of Petroleum Geologists Correlation Chart Series, 1 sheet.

Collier, A. J., 1919, The Nesson anticline, Williams County, North Dakota: U.S. Geological Survey Bulletin 691-G, p. 211-217.

Dove, L. P., 1922, The geology and structure of the east side of the Nesson anticline: Quarterly Journal of the University of North Dakota, v. 12, no. 3, p. 238-249.

Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C. G., 1982, Geological development, origin, and energy mineral resources of Williston basin, North Dakota: American Association of Petroleum Geologists Bulletin, v. 66, p. 989-1020.

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, G. A. G., Smith, A. G., and Walters, R., 1982, A geologic time scale: Cambridge University Press, Cambridge, 131 p.

Laird, W. M., 1946, The subsurface stratigraphy of the Nesson anticline: North Dakota Geological Survey Bulletin 21, part II, p. 11-25.

Laird, W. M., and Folsom, C. B., Jr., 1956, North Dakota's Nesson anticline: North Dakota Geological Survey Report of Investigation 22, 12 p.

Laird, W. M., Hanson, M., Folsom, C. B., and Anderson, S.B., 1955, The Beaver Lodge and Tioga fields, Mountrail and Williams Counties, North Dakota; In: American Association of Petroleum Geologists, Rocky Mountain Section 1955 Geological Record, p. 37-54.

Nevin, C., 1946, The Keene dome, northeast McKenzie County, North Dakota: North Dakota Geological Survey Bulletin 21, part I, p. 1-10.

North Dakota Geological Society, 1959, Nesson anticline: North Dakota Geological Society, Bismarck, North Dakota, 81 p.

SALT DISSOLUTION AND TECTONICS, SOUTH-CENTRAL SASKATCHEWAN[1]

GREGORY J. McTAVISH AND LAURENCE W. VIGRASS
Department of Geology and Energy Research Unit
University of Regina
Regina, Saskatchewan
S4S 0A2

ABSTRACT

Subsurface dissolution of the Middle Devonian Prairie Evaporite is a major structure-forming process in south-central Saskatchewan. The dissolution phenomenon is a multistage process of salt removal that entails collapse of the overlying sedimentary column and accelerated sedimentation into surface depressions produced during collapse. The process is important because it affects the sedimentation and diagenesis of younger strata and may produce structures suitable for petroleum entrapment.

Linear dissolution trends which migrate laterally with time occur within the South Regina and Hummingbird Troughs. Analysis of structure contour, isopach and residual maps has yielded a chronology of dissolution events. Salinities (TDS) increase and hydraulic heads decrease as one moves eastward from a large salt-free area into the main salt body. Both composition of subsurface waters and fluid pressures suggest an upwelling of formation waters within the Hummingbird Trough.

Within the map-area, two differing situations appear to affect salt dissolution. In the northeast, salt removal appears to be localized above porous and permeable Winnipegosis mounds of the Elk Point Basin. In the southwestern part of the study-area, underlain by the Winnipegosis marginal carbonate shelf, it seems likely that dissolution was localized by fracturing associated with diastrophic (deep-seated) structures.

INTRODUCTION

For many years subsurface solution of Devonian and Mississippian evaporites has been recognized as an important geological process in the Williston Basin area. Evaporite solution breccias were described in Upper Devonian rocks in Montana by Sloss and Laird (1947) and in Middle Devonian strata of Manitoba and Saskatchewan by Baillie (1953). In an early written account of oil-field type structures formed by subsurface salt removal, Bishop (1954, p. 481-483) described salt dissolution in the Venn area of western Saskatchewan. Bishop showed that dissolution at Venn occurred mainly during pre-Jurassic and post-Cretaceous times. Important subsequent contributions on the subject include those of DeMille et al (1964), Smith and Pullen (1967), Swenson (1967), Holter (1969) and Gendzwill (1978). Subsurface dissolution of salt is important because of the effect it has had on the evolving sedimentary fill of the basin. Pooling at several oil fields is related directly to the dissolution phenomenon.

The present study examines dissolutioning of Prairie Evaporite (Middle Devonian) in part of the northern Williston Basin. The study-area encompasses 28,000 km² (11,000 square miles) of south-central Saskatchewan, northeastern Montana and northwestern North Dakota (Fig. 1). Salt dissolution is widespread in the area and its history complex. The main method of study has involved construction of structure and isopach maps using well defined contacts between conformable lithic units. Anomalies were sharpened by removing regional effects and deriving residual maps. Hydrogeology was examined, utilizing pressures and water compositions derived from selected tests run on high permeability zones in the water leg. Geophysical logs and drill-stem test information were available on 1,242 boreholes. Main objectives of the study were to determine extent and timing of Prairie Evaporite dissolution, to assess the part that hydrogeology has played in salt removal, and to evaluate the effect of diastrophic structures on salt dissolution. Much of the work was done by McTavish as part of M.Sc. requirements at the University of Regina.

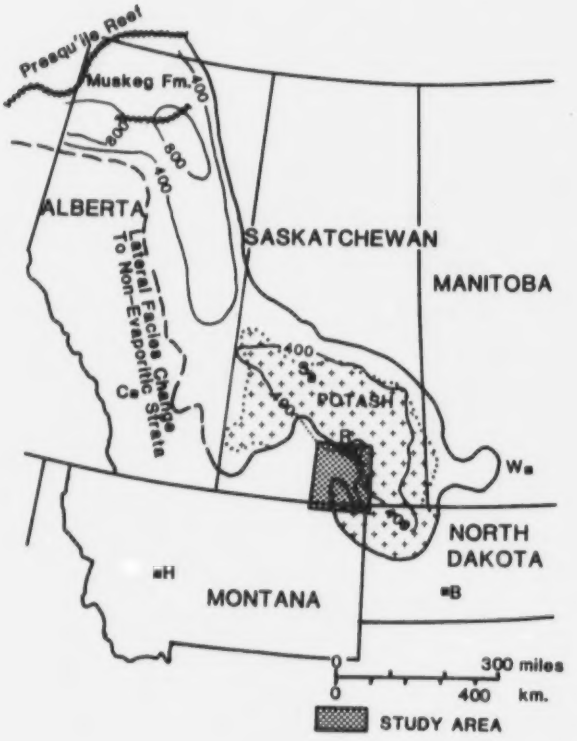


Fig. 1 Location map showing regional isopach of Prairie Evaporite, interval 400 ft. (after Holter, 1969). Note that the 400-ft. isopach is restored in part.

Salt removal in much of the study area occurred aperiodically, starting soon after deposition of the Prairie Evaporite and continuing to the present. Linear dissolution troughs have migrated laterally with time. Hydrogeological control of dissolution is suggested by present fluid movement paths. Salt removal appears to have been localized by Winnipegosis mounds in the northeast and linear diastrophic structures in the southwest.

[1]Contribution No. 157 of Energy Research Unit

GEOLOGICAL FRAMEWORK AND PETROLEUM OCCURRENCE

Preserved Phanerozoic rocks thicken from about 2 km (6,500 ft.) at the north end of the study-area to about 4 km (13,000 ft.) at the south end. The sedimentary sequence (Fig. 2) is divisible into three gross lithological units: a basal clastic unit (Cambrian-Middle Ordovician) of sandstone and shale, a medial carbonate-evaporite unit (Middle Ordovician-Mississippian) of dolomite, limestone, anhydrite, halite and potash salts, and an upper clastic unit (Triassic or Jurassic to Quaternary) of shale and sandstone (Christopher et al, 1971). The succession is interrupted by several unconformities. Detrital rocks of Pennsylvanian and Permian age, widespread in the southern Williston Basin, are largely absent from the map-area.

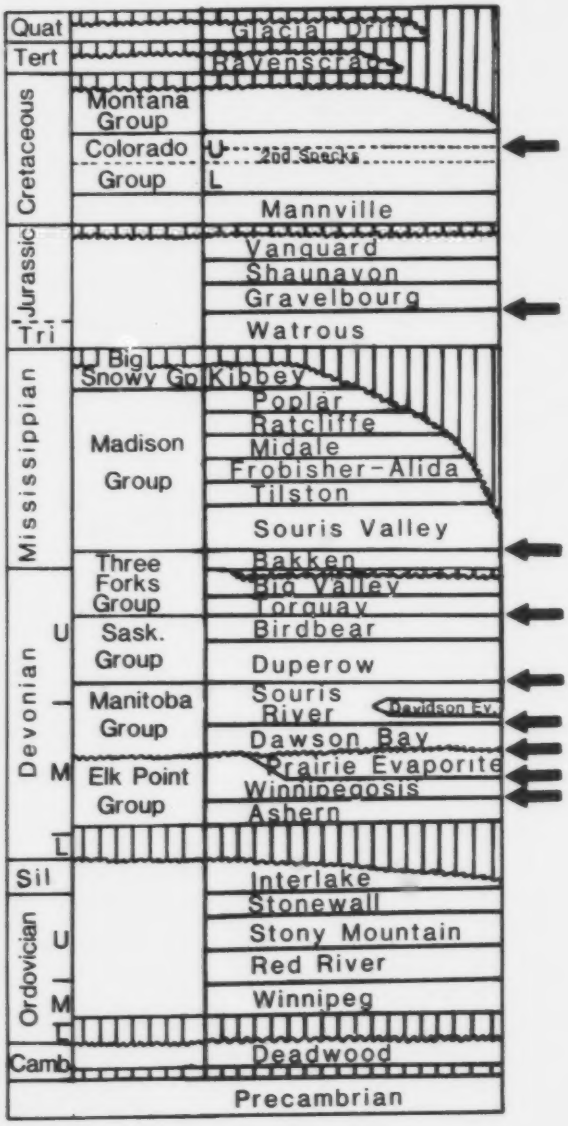


Fig. 2 Rock-stratigraphic units in South-Central Saskatchewan. Arrows show main horizons used in preparing isopach and structure maps.

In the study-area the surface of Precambrian basement, which dips southward at about 8 m/km (45 ft./mile), appears to be relatively smooth. The southward dip is interrupted locally by low-relief structures of diastrophic origin; the Outlook structure of Devonian age (Wilson et al, 1963) is a noteworthy example. Most local structures mapped in post-Middle Devonian strata are attributable to salt dissolution.

The present study largely concerns the dissolution of the Middle Devonian Prairie Evaporite, a late-stage deposit in the Elk Point depositional basin which lay between central North Dakota and northwest Alberta (Fig. 1). The Prairie Evaporite, up to 300 m (1000 ft.) thick in northern Alberta, is more than 130 m (430 ft.) thick in the study-area. Extensive dissolution of Prairie Evaporite has occurred along the northeastern and eastern side of the Elk Point Basin. Distribution of potash salts and restoration of evaporite isopachs suggest that Prairie Evaporite originally occurred below a large part of the map-area (Fig. 1). A salient of salt, the Roncott Remnant (Roncott Anticlinorium of Christopher, 1961), extends northward from Montana into Saskatchewan. Salt-free areas which have involved subsidence and collapse of overlying strata include the South Regina, Hummingbird and Coronach Troughs (Fig. 3; DeMille et al, 1964; Broughton, 1977).

Since the 1956 discovery of oil at Outlook, Montana and Roncott, Saskatchewan, nearly 11 x 106 m^3 (69 million barrels) of oil and 3.25 x 108 m^3 (11.5 billion cubic ft.) of gas have been produced from 24 fields within the study-area (Fig. 4; Saskatchewan Energy and Mines, 1985, and Petroleum Information Corporation, 1980). Seventeen of the twenty-four

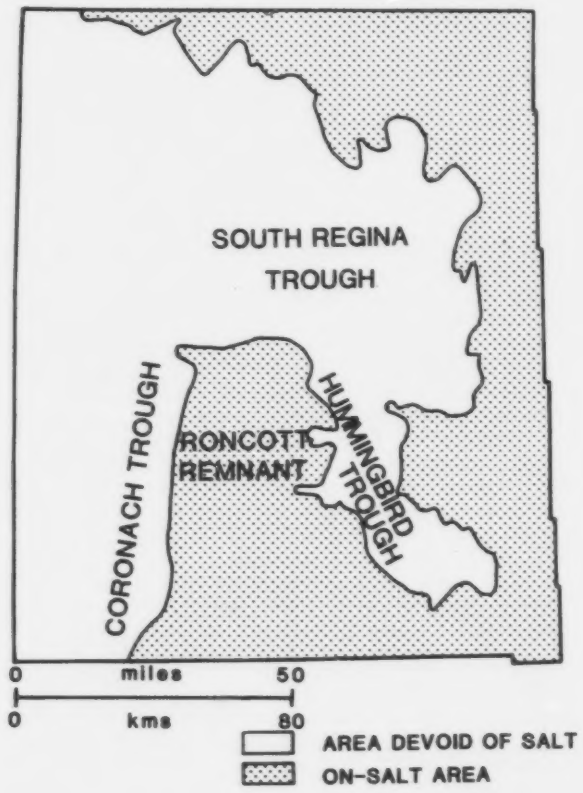


Fig. 3 Distribution of Prairie Salt within the study-area (see text for explanation).

Fig. 4 Oil pools in the study-area.

fields produce, at least partly, from strata of Mississippian age. Trapping mechanisms range from structural traps attributable to basement uplift (Outlook Field; Wilson et al, 1963) or multistage salt solutioning (Hummingbird, Lake Alma and Outlook Fields) to structural-stratigraphic traps (Freda Lake, Skinner Lake, Neptune and Oungre Fields; Hartling et al, 1982).

SALT DISSOLUTION AND ITS RECOGNITION

Salt dissolutioning is the process by which evaporitic strata are dissolved by formation waters (groundwater). The removal of evaporites results in fracturing, collapsing, and subsiding of overlying strata with accompanying accelerated sedimentation into surface depressions.

Extent and timing of dissolution events are determined from isopach and structure maps. The Prairie Evaporite section is absent or abnormally thin in areas where salt has been removed by subsurface dissolution. Basins or troughs are produced in at least some of the overlying strata. Local thinning of the salt is balanced by local thickening of the strata accumulating at the surface at the time of salt dissolution. Isopach and structural anomalies can be sharpened by using trend surface analysis to remove regional effects and to derive residual maps. In this study, second-order (second-degree) regional trends of thickness and structure were removed to leave second-order residual maps (Krumbein and Graybill, 1965). Seismic information was not used in this study but its inclusion would enhance the identification and mapping of anomalous areas.

Many early workers considered that salt dissolution occurred during a single event of evaporite removal which produced a large, local structural low; this "solution low" would contain a simple thickened lens of sedimentary fill deposited during the time of salt dissolution. Smith and Pullen (1967) demonstrated that complex localized domal structures were produced through multiple-stage salt dissolution with collapse. They showed that, in the Hummingbird Field, the dome which acts as a structural trap is the result of local dissolution with thickening of Devonian and Mississippian strata. Jurassic and Cretaceous removal of salt from the surrounding area has caused the top of the thickened strata in the core of the structure to be higher than correlative beds in the collapsed annulus (see Fig. 8 to 12 of Smith and Pullen, 1967).

Good marker horizons that are easily identified and readily traced from well to well were used in the study (Fig. 2). Significant unconformities were avoided as markers so that paleo-erosional effects were minimized in the interpretation of the isopach and structure maps.

ISOPACH-STRUCTURE MAPS AND SALT DISSOLUTION FEATURES

MANITOBA GROUP

Subsurface dissolution began during the Middle Devonian when the Prairie Evaporite was buried to shallow depth (DeMille et al, 1964). The second-order residual isopach of the Dawson Bay Formation (Fig. 5) shows alternating thicks and thins that trend northwest in the southern Hummingbird Trough. Other isopach thicks occur in the vicinity of Outlook Field, Montana, and north of Roncott Field, Saskatchewan (Fig. 5). A residual isopach of the Souris River Formation (Fig. 6) shows local thick residuals in the southern end of the Hummingbird Trough, in the salt-free area north of the Roncott Remmant (Tp. 12 Rge. 22 W2M), and in the extreme north-central part of the area (Tp. 17 Rge. 24 W2M).

The positive thickness anomalies on the Dawson Bay and Souris River isopach maps are considered to reflect subsurface salt dissolution that began during the Middle Devonian and continued into early Late Devonian. Most of the dissolution features are aligned along a linear trend that is subparallel to the Hummingbird Trough (Fig. 7).

SASKATCHEWAN AND THREE FORKS GROUPS

The second-order residual isopach map of the Saskatchewan Group (Duperow and Birdbear Formations) shows anomalous thicks at the Hummingbird, Lake Alma and Outlook oilfields (Fig. 8). Larger positive (thick) areas cover parts of the Roncott Remnant and the southern South Regina Trough. Isopach maxima of apparent small areal extent occur in the northwest (Tp. 14 Rge. 25 W2M. and Tp. 17 Rge. 24 W2M).

The residual isopach map of the Three Forks Group (Torquay, Big Valley and Bakken Formations) reveals anomalous thickening in several areas (Fig. 9):

1) Hummingbird, Lake Alma and Outlook oilfields,
2) arcuate areas at and near the north end of the Roncott Renmant,
3) a large area extending from the South Regina Trough east-southeast into the main salt area, and
4) small isolated areas in the northwest (Tp. 14 Rge. 27 W2M and Tp. 17 Rge. 25 W2M).

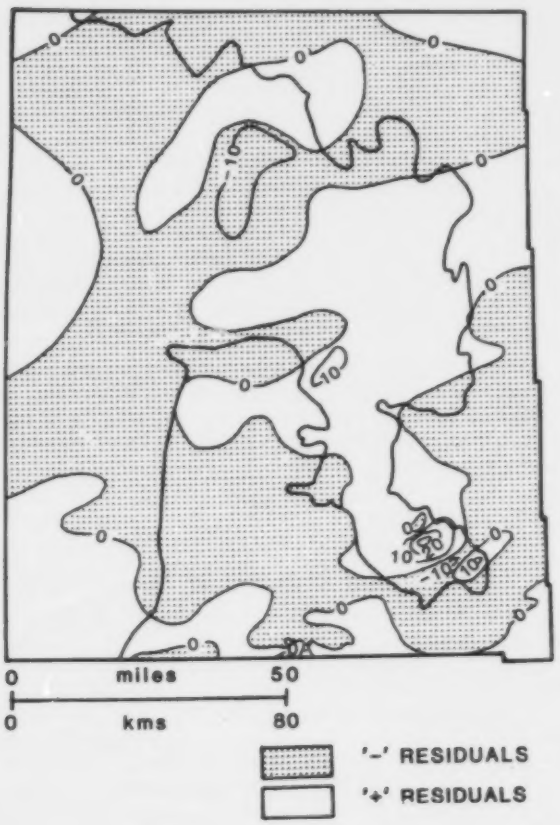


Fig. 5 Second-order residual isopach of the Dawson Bay Formation based on borehole information. Negative residuals (thins) are patterned, interval 10 m.

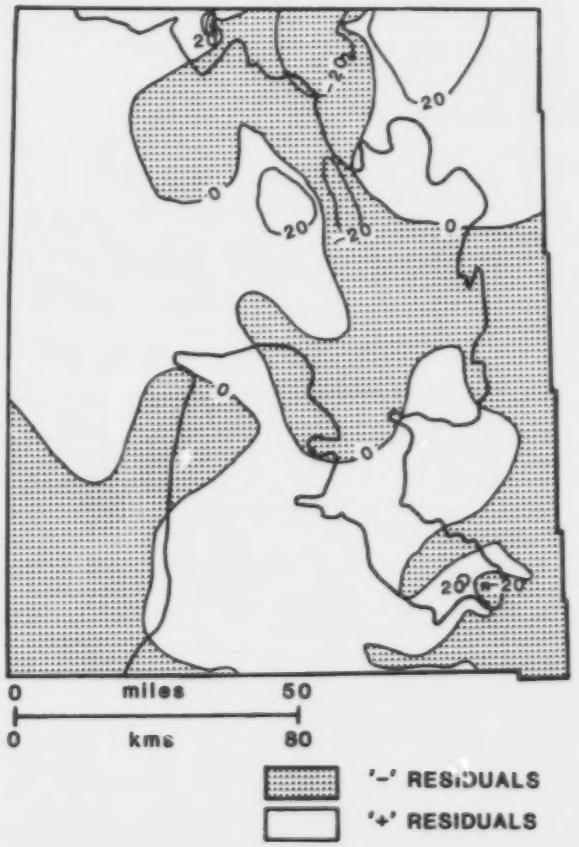


Fig. 6 Second-order residual isopach map of the Souris River Formation. Negative residuals are patterned, interval 20 m.

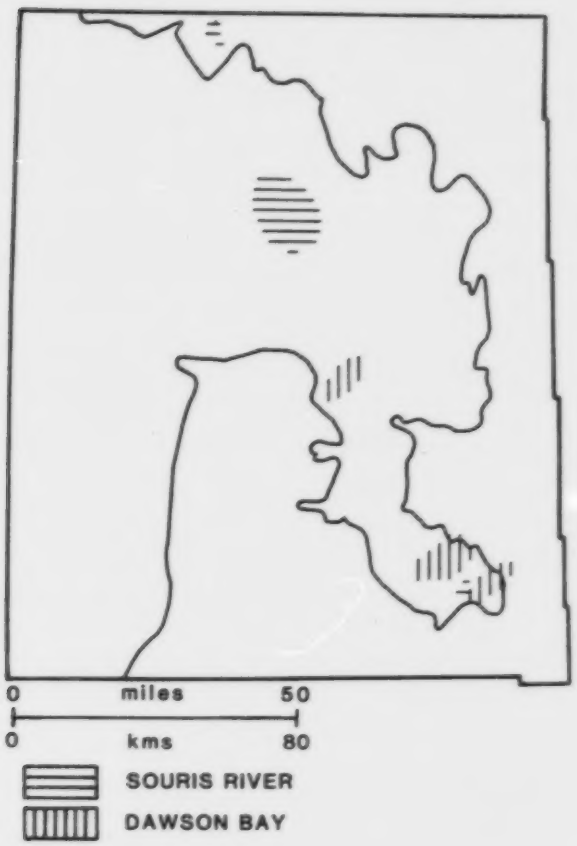


Fig.7 Extent of subsurface dissolution (as indicated by isopach maps) accompanying deposition of A) Dawson Bay and B) Souris River Formations (Middle and Upper Devonian).

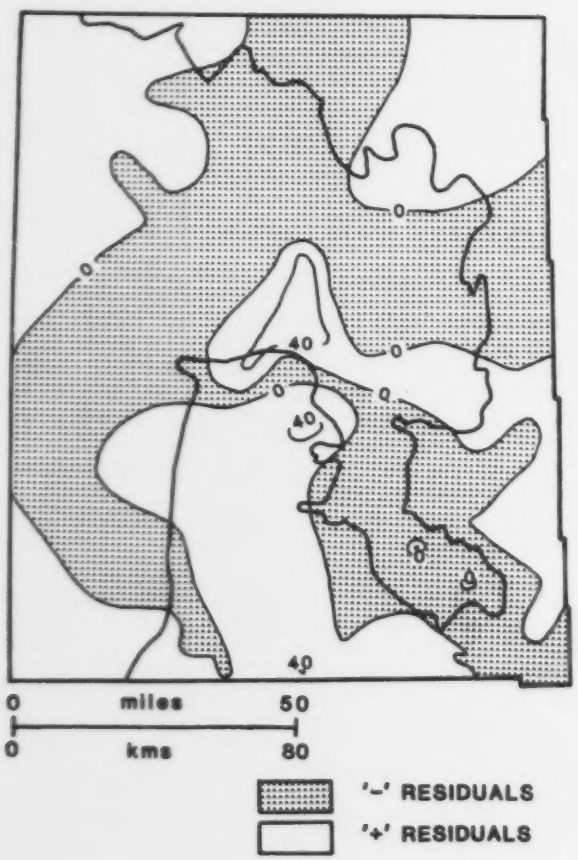


Fig. 8 Second-order residual isopach map of Duperow and Birdbear Formations (Saskatchewan Group). Negative residuals are patterned, interval 40 m.

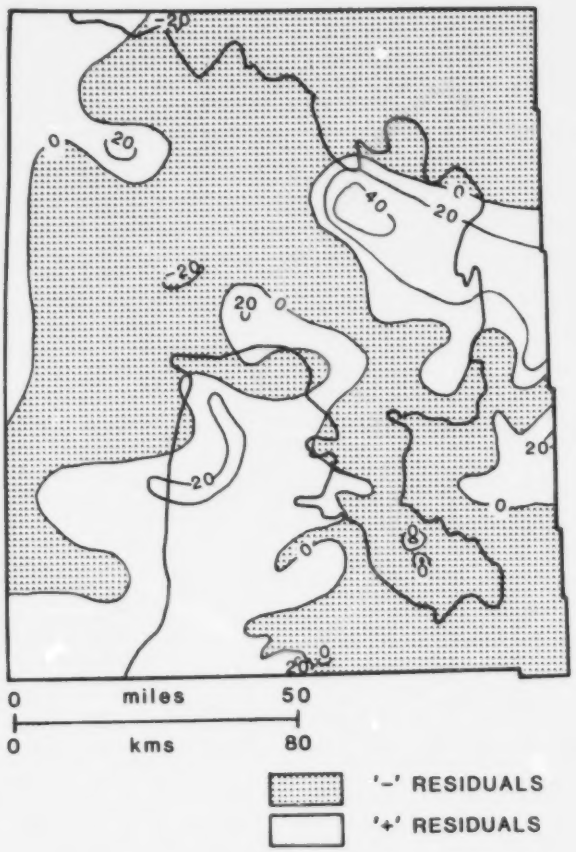


Fig.9 Second-order residual isopach map of Torquay, Big Valley and Bakken Formations (Three Forks Group). Negative residuals are patterned, interval 20 m.

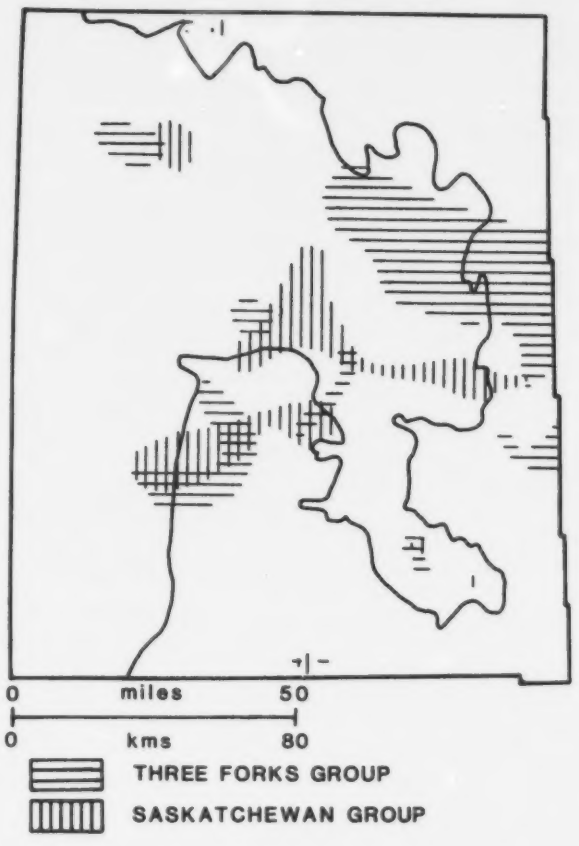


Fig.10 Extent of subsurface dissolution accompanying deposition of A) Saskatchewan Group and B) Three Forks Group (Upper Devonian).

The positive (thick) isopach anomalies are considered to reflect largely subsurface salt dissolution that accompanied deposition of the Saskatchewan and Three Forks Groups during the Late Devonian. Salt dissolution occurred in restricted areas at the south but was more widespread in the central part of the study-area. Near the south end of the South Regina Trough, dissolution appears to have occurred along linear belts that trend west-northwest (Fig. 10).

MADISON-WATROUS AND GRAVELBOURG-SECOND WHITE SPECKS

The second-order residual isopach map that includes the Madison and Big Snowy Groups (Mississippian) and the Watrous Formation (Triassic?-Middle Jurassic) shows pronounced thickening in the northern part of the South Regina Trough and the southern portion of the Hummingbird Trough (Fig. 11). The residual isopach map of strata from the base of the Gravelbourg Formation (Middle Jurassic) to the top of the Second White Speckled Shale (Upper Cretaceous) is rather more ambiguous but defined positives (thicks) occur at the southeast end of the South Regina Trough, at the north end of the Hummingbird Trough, and northwest of the Roncott Remmant (Tp. 10 Rge. 25 W2M) (Fig. 12).

Both isopach intervals include within them major unconformities. The interval from the base of the Madison Group to the top of the Watrous Formation includes the regional sub-Watrous unconformity. No doubt there have been some changes of thickness of this stratal package since Middle Jurassic time as a result of compaction and dissolution of Madison salt but, in general, the isopach can be regarded as a paleostructural map of the base of the Madison during Middle Jurassic time. Similarly the interval from the base of the Gravelbourg Formation to the top of the Second White Speckled Shale includes the regional sub-Mannville (Lower Cretaceous) unconformity and the isopach can be regarded as a paleostructural map on the base of the Gravelbourg during Late Cretaceous time.

Positive (thick) isopach anomalies are interpreted to reflect subsurface dissolution of salt (Fig. 13). Major dissolution occurred in the South Regina and Hummingbird Troughs during Mississippian to Middle Jurassic time, presumably largely during the episode of basinal uplift that is represented by the sub-Watrous unconformity. Salt solution was extensive during Middle Jurassic to Late Cretaceous time, presumably occurring mainly during the episode of basin uplift that is represented by the sub-Mannville unconformity.

STRUCTURE OF SECOND WHITE SPECKS

The second-order residual structure map of the Second White Speckled Shale (Upper Cretaceous) shows a pronounced negative anomaly (structural low) extending southwest and

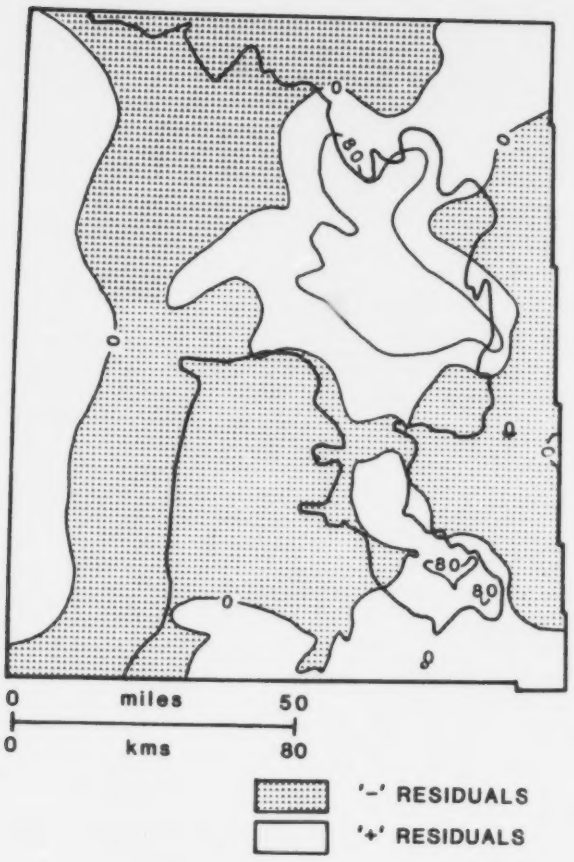


Fig. 11 Second-order residual isopach map of combined Madison Group, Big Snowy Group, and Watrous Formation. Negative residuals are patterned, interval 80 m.

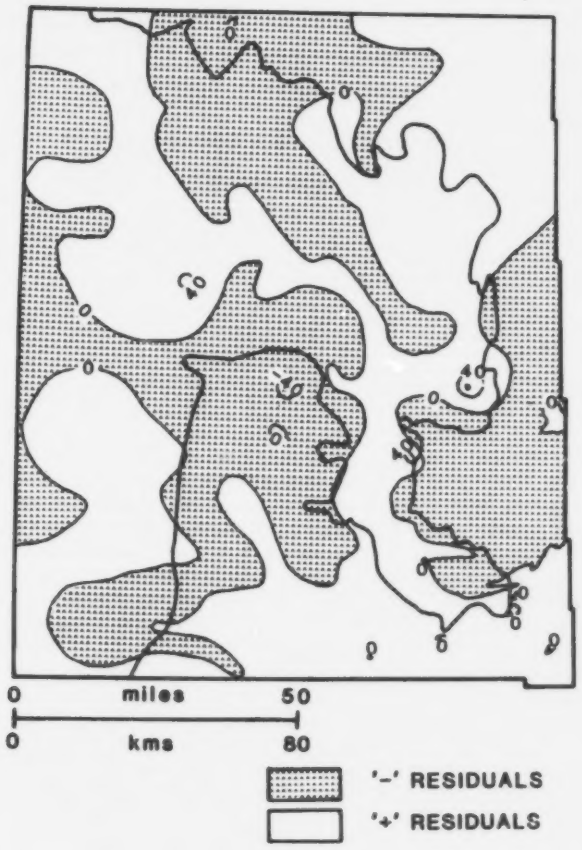


Fig. 12 Second-order residual isopach map of rocks from the base of the Gravelbourg Formation to the top of the Second White Speckled Shale. Negative residuals are patterned, interval 40 m.

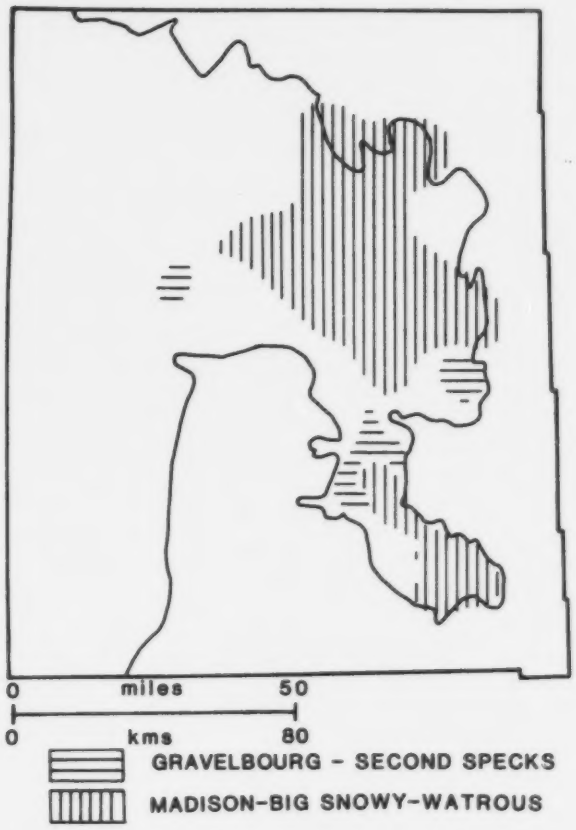


Fig. 13 Extent of subsurface dissolution accompanying deposition of A) combined Madison-Big Snowy-Watrous (Mississippian-Middle Jurassic), and B) Gravelbourg - Second White Specks (Middle Jurassic-Upper Cretaceous).

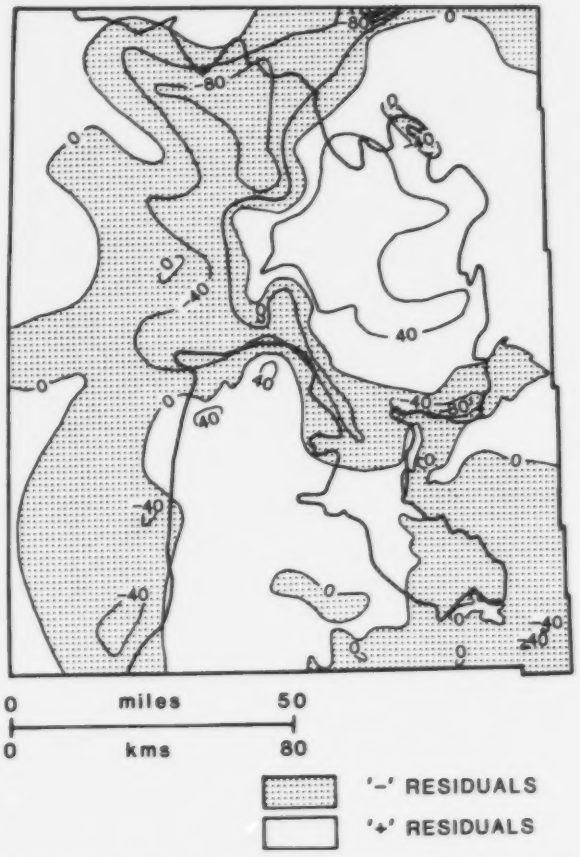


Fig. 14 Second-order residual structure map of the top of the Second White Speckled Shale. Negative residuals (lows) are patterned, interval 40 m.

south from Regina (Tp. 17 Rge. 19 W2M) to the north end of the Roncott Remnant (Fig. 14). The anomaly then bifurcates with one branch extending south along the Coronach Trough and a second branch extending eastward to Tp. 6 Rge. 17 W2M. A small structural low occurs within the salt-free area in Tp. 14 Rge. 18 W2M (Fig. 14).

In areas where salt is thin or absent, the anomalous structural lows are considered to reflect salt dissolution that has occurred since deposition of the Second White Speckled Shale during the Late Cretaceous (Fig. 15). Exact timing of the salt removal is difficult to ascertain because good marker horizons are restricted areally. Strata in the Ravenscrag Formation (Paleocene) are thickened along the Coronach Trough (Broughton, 1979; Whitaker et al, 1978) so that salt dissolution in the area is at least partly of early Tertiary age. Depressions on the eroded surface of Tertiary and Cretaceous bedrock, now infilled by Quarternary sediment, are common in southern Saskatchewan. Several of these depressions have been related genetically to the subsurface dissolution of Prairie Salt during the Pleistocene or Recent Epochs (Christiansen, 1967, 1971a, 1971b).

SPATIOTEMPORAL EXPANSION OF DISSOLUTION AREAS

The lateral migration or expansion of dissolution channels with time has been described by Christopher (1961) and Kent (1968). In the South Regina Trough, the earliest solution features migrated southward during deposition of the Saskatchewan Group and then northward during Three Forks deposition (Fig. 10). The northern area of salt dissolution expanded and shifted southward during the Mississippian to Middle Jurassic episode (Fig. 13). Small isolated areas in the southern part of the trough were affected by dissolution during Middle Jurassic to Late Cretaceous (Fig. 13). A large area at the western edge of the South Regina Trough which extends southward along the western edge of the Roncott Remnant, has been dissolved since Late Cretaceous time (Fig. 15). During the Late Cretaceous-Cenozoic episode, a dissolution trend wrapped around the north end of the Roncott Remnant and extended eastward at the south end of the South Regina Trough (Fig. 15).

In the Hummingbird Trough and surroundings, dissolution during the Middle and Late Devonian occurred largely in isolated areas associated with the Hummingbird, Lake Alma and Outlook Fields (Figs. 7, 10). Dissolution areas expanded and shifted northward during the Mississippian to Middle Jurassic, and shifted even farther to the northwest during the Middle Jurassic - Late Cretaceous episode (Fig. 13). Post-Late Cretaceous solution is not prominent in the Hummingbird Trough.

A more general view of the expansion and shifting of salt dissolution during Middle Devonian - Recent time is revealed in Figure 16, a map showing interpretation of age of earliest

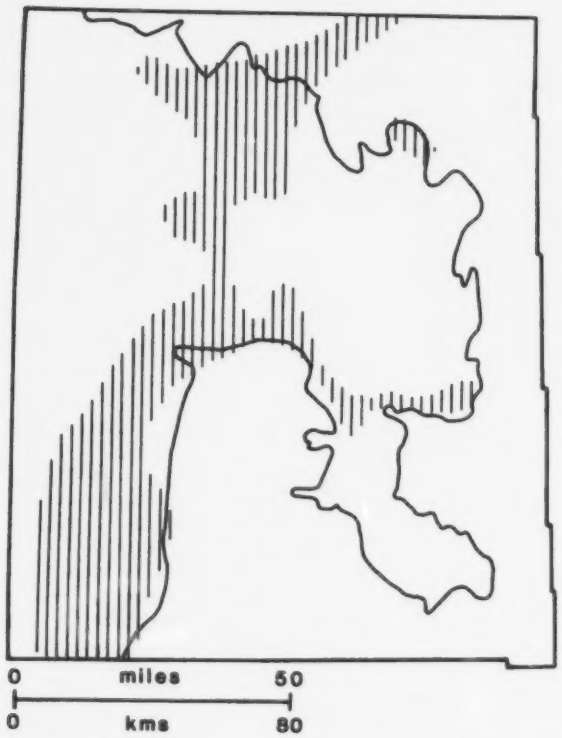


Fig. 15 Extent of subsurface dissolution (as indicated by structural mapping) since the deposition of the Second White Speckled Shale (Upper Cretaceous).

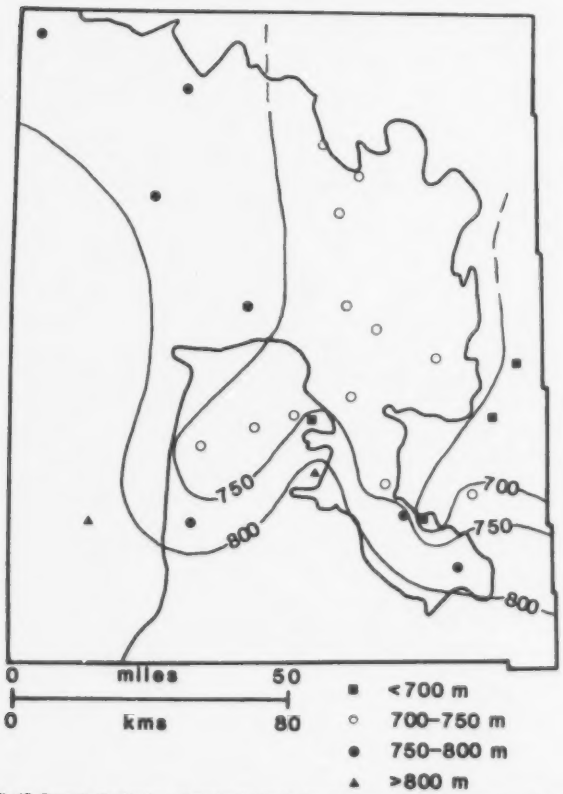


Fig.17 General distribution of hydraulic heads for the Souris River Formation and the Saskatchewan and Three Forks Groups (Devonian). Hydraulic heads are calculated for water density of 1,000 kg/ m³.

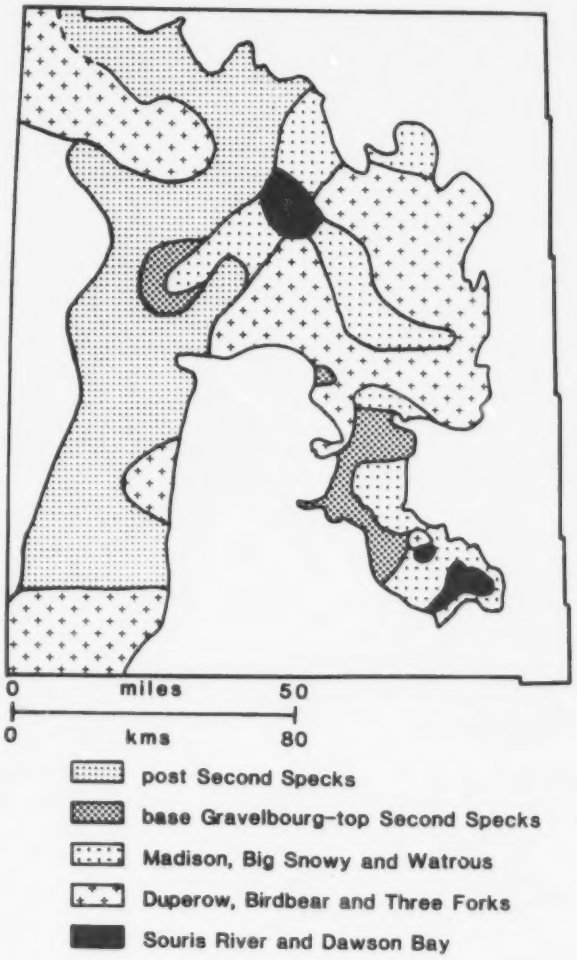

0 miles 50
0 kms 80
post Second Specks
base Gravelbourg–top Second Specks
Madison, Big Snowy and Watrous
Duperow, Birdbear and Three Forks
Souris River and Dawson Bay

Fig. 16 Map showing the time of inception of salt dissolution in the salt-free area

significant salt dissolution in the salt-free area. Locally the beginning of dissolution is delimited by anomalies that are less distinct than those shown in Figures 7, 10, 13 and 15.

HYDROGEOLOGY

More than 1,634 drill-stem tests have been run in the Canadian segment of the study-area. Quality checks were used to select data on hydraulic head and total dissolved solids (TDS) using drill-stem tests run on high permeability zones in the water leg. From this selected data, it is apparent that salinities (TDS) increase and hydraulic heads decrease in Devonian strata as one proceeds from the large salt-free area in the west toward the main salt body in the east (Figs. 17, 18). All available salinity (TDS) data plotted on a west-east structural section (Fig. 19) suggest upwelling of formation water within the Hummingbird Trough. Section A-A' also suggests that a "halo" of saline water extends westward from the Prairie Evaporite preserved in the Roncott Remant; in this area, waters with more than 100,000 mg/ litre of total dissolved solids occur largely in Interlake, Winnipegosis and Dawson Bay strata (Fig. 19).

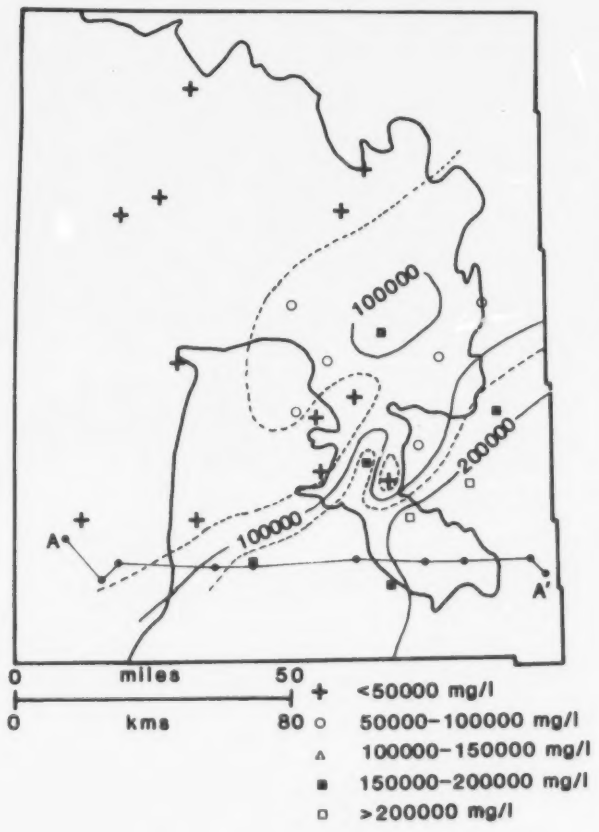


Fig.18 General distribution of total dissolved solids (mg/litre) for the Souris River Formation and the Saskatchewan and Three Forks Group (Devonian). Line of section A-A' is shown.

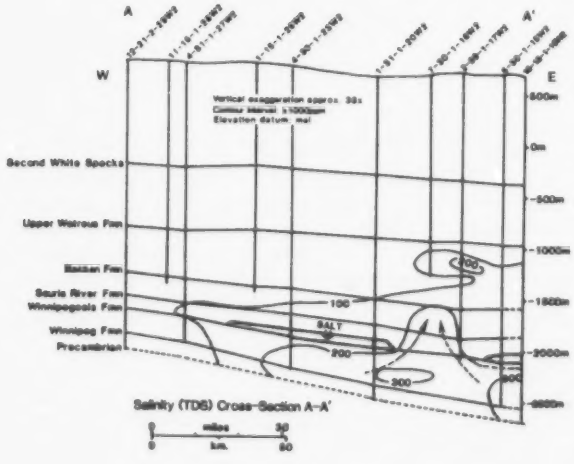


Fig. 19 Schematic diagram showing total dissolved solids (kg/m³) for Section A-A.

GEOLOGICAL CONTROLS OF SALT DISSOLUTION

DeMille et al (1964) acknowledged that dissolution is enhanced by porous and permeable formations below the salt which allow fresh water to be transported to the site of dissolution and saline water to be transported away. Bishop (1954) and Gendzwill (1978) submitted that permeable Winnipegosis carbonate mounds, which occur in the Elk Point Basin, serve to initiate salt removal. According to this hypothesis, groundwater moving through the carbonate mound causes dissolution at the base of the salt which proceeds until pore space in the mound is clogged by insoluble material from the evaporite. A very large flux of water is required to dissolve the salt in its entirety. Conceivably, salt dissolution over a plugged mound might be rejuvenated if insoluble material was flushed out by increased water flow.

Winnipegosis paleogeography shows that carbonate mounds are restricted to the northeastern part of the map-area (Fig. 20). Some mechanism other than carbonate-mound control must have been responsible for the widespread salt dissolution that occurred above the Winnipegosis marginal carbonate shelf (Fig. 20). In the larger part of the study-area, salt dissolution may be attributable to groundwater movement along fractures that interconnect porous and permeable formations which occur both below and above the Prairie Evaporite.

Some fracture systems penetrating Phanerozoic rocks may reflect more-or-less ubiquitous jointing in the underlying Precambrian basement rocks. Conceivably these fracture systems, consisting of two fracture sets which trend northwest and northeast, are revealed at the surface by photo-lineaments

Fig.20 Winnipegosis paleogeography (Middle Devonian) (adapted from Fuller and Porter, 1969).

(Figs. 4, 6 and 7 of Mollard, 1986). There is also evidence that the Phanerozoic strata have been affected by brittle faults and ductile shear zones in the Precambrian basement rocks. In southern Hummingbird Trough, a seismic study by Surjik and Hobson (1964) has revealed an anomalous zone trending northwest through Tp. 1 Rge. 19 W2M that probably represents fault-line valleys on the eroded basement surface. About 11 km (7 miles) to the northwest, the Dome et al Jim Creek 4-32-2-20 well encountered more than 150 m (500 ft.) of granite wash, presumably deposited in a fault-line valley on the basement surface. Basement faults and shear zones may have been reactivated during Phanerozoic time. DeMille et al (1964) reported salt dissolution coincident with the Precambrian Nemo-Estes gravity-magnetic trend. Camfield and Gough (1977) showed the North American Central Plains (NACP) electroconductivity anomaly to be associated with the Hummingbird Trough. The NACP is considered to reflect a major basement discontinuity, possibly reflecting hydrous sedimentary material subducted along a plate margin during Precambrian time (Lewry et al, 1985).

Other structural features involving the eroded surface of Precambrian basement rocks may reflect deep-seated structural movements during Phanerozoic time. Sawatzky et al (1960) and Wilson et al (1963) reported numerous Precambrian high features associated with areas of salt removal. It has been reported that these structural features are prevalent south of the study area in northeast Montana where lower Paleozoic strata are warped into plunging anticlines (noses) as a result of local uplift of basement rocks. Kent (1973, 1974) indicated that salt dissolution structures elsewhere are associated with positive structures mapped by seismic and with bedrock lineaments. Modern seismicity related to the basement of the Hummingbird Trough has been reported by Horner and Hasegawa (1978).

EFFECT OF SALT DISSOLUTION ON SEDIMENTATION AND DIAGENESIS

There is ample evidence that the effects of subsurface salt dissolution extend upward to the surface, resulting in accelerated sedimentation into surface depressions. Hartling et al (1982) reported a thicker and more micritic Oungre Zone of the Ratcliffe Member (Mississippian) in the Hummingbird Trough than elsewhere. Whitaker et al (1978) and Broughton (1979) have reported anomalous sedimentation in the Ravenscrag (Paleocene) coal measures along the Coronach Trough. Kent (1968) has described anomalous thickening (to 14.5 m or 48 ft.) of the lower Birdbear carbonates related to Late Devonian salt dissolution in Lsd. 13-4-25-8 W3M; the anomalous lower Birdbear at this location consists of alternating laminations of kerogen-rich and kerogen-poor lime mudstones. Documentation of such local effects on sedimentation is rare.

As a result of subsurface dissolution of Prairie Salt, there has been collapse, fracturing and dilation of overlying strata. Anomalous diagenetic effects would be expected in younger strata but these have not been widely reported in the literature. At Hummingbird Field, there has been obvious preferred dolomitization in the Birdbear (Upper Devonian) and Ratcliffe (Mississippian) oil reservoirs. Such dolomitization, related to structural relief produced by salt dissolution, has produced many areas of enhanced reservoir development (D.M. Kent, personal communication).

CONCLUSIONS

Analysis of isopach and structure maps of south-central Saskatchewan shows that subsurface salt dissolution began soon after deposition of the Prairie Evaporite and has continued aperiodically to the present. Temporal expansion and lateral shifting of areas of dissolution are most evident in the South Regina and Hummingbird Troughs, areas presently devoid of Prairie Salt. Absence of isopach anomalies near the western edge of the study area suggests that significant thicknesses of Prairie Evaporite were not deposited in south-central Saskatchewan west of longitude 106°W.

Presumably, the history of salt dissolution is closely tied to paleohydrology. At present, hydraulic heads decrease and salinity increases as one progresses from the salt-free area at the west edge of the study-area to the main salt body at the east edge. There is a suggestion of upwelling of formation waters in the Hummingbird Trough.

In the northeastern part of the study-area, dissolution of Prairie Salt may have been initiated above isolated Winnipegosis carbonate mounds. In the southwest, where the Winnipegosis consists of a marginal carbonate shelf, salt solution was presumably initiated along fracture systems penetrating the salt; at least some of the fracture systems are related to Phanerozoic movement along basement faults and shear zones.

ACKNOWLEDGEMENTS

This paper constitutes a portion of the M.Sc. thesis currently being written by Greg McTavish at the University of Regina, under the supervision of Dr. L.W. Vigrass. Access to information and facilities at Saskoil and Saskatchewan Energy and Mines are greatly appreciated. We thank Chris Blair for manuscript preparation. Financial support was provided through a postgraduate scholarship to McTavish from the Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

Baillie, A.D., 1953, Devonian System of the Williston Basin area: Man. Dept. Mine and Nat. Res., Mines Branch Publ. 52-5.

Bishop, R.A., 1954, Saskatchewan exploration progress and problems. In: L.M. Clark, ed., Western Canada Sedimentary Basin Symposium: AAPG Ralph Leslie Rutherford Memorial Volume, p. 474-485.

Broughton, P.L., 1977, Origin of coal basins by salt solution: Nature, v. 270, p. 420-423.

Broughton, P.L., 1979, Origin of coal basins by salt solution tectonics in western Canada: Unpub. Ph.D. thesis, University of Cambridge, Cambridge, England.

Camfield, P.A., and D.I. Gough, 1977, A possible Proterozoic plate boundary in North America: Can. J. Earth Sci., v. 14, p. 1229-1238.

Christiansen, E.A., 1967, Collapse structures near Saskatoon, Saskatchewan, Canada: Can. J. Earth Sci., v. 4, p. 757-767.

Christiansen, E.A., 1971a, Geology and groundwater resources of the Regina area (72I), Saskatchewan: Saskatchewan Research Council Map 13, 1:250,000.

Christiansen, E.A. 1971b, Geology of the Crater Lake collapse structure in southeastern Saskatchewan: Can. J. Earth Sci., v. 8, p. 1505-1513.

Christopher, J.E., 1961, Transitional Devonian-Mississippian formations in southern Saskatchewan: Sask. Dept. of Min. Res. Report No. 66.

Christopher, J.E., D.M. Kent, and F. Simpson, 1971, Hydrocarbon potential of Saskatchewan: Sask. Dept. of Min. Res. Report No. 157.

DeMille, G., J.R. Shouldice, and H.W. Nelson, 1964, Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Geol. Soc. of America Bull., v. 75, p. 307-316.

Fuller, J.G.C.M., and J.W. Porter, 1969, Evaporite formations with petroleum reservoirs in Devonian and Mississippian of Alberta, Saskatchewan, and North Dakota: AAPG Bull., v. 53, p. 909-926.

Gendzwill, D.J., 1978, Winnipegosis mounds and Prairie Evaporite Formation of Saskatchewan - seismic study: AAPG Bull., v. 62, p. 73-86.

Hartling, A., A. Brewster, and G. Posehn, 1982, The geology and hydrocarbon trapping mechanisms of the Mississippian Oungre zone (Ratcliffe Beds) of the Williston Basin. In: J.E. Christopher and J. Kaldi, eds., Fourth International Williston Basin Symposium, Saskatchewan Geological Society Special Publication 6, p. 217-223.

Holter, M.E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Sask. Dept. of Min. Res. Report No. 123.

Horner, R.B., and H.S.Hasegawa, 1978, The seismotectonics of southern Saskatchewan: Can. J. Earth Sci., v. 15, p. 1341-1355.

Kent, D.M., 1968, The geology of the Upper Devonian Saskatchewan Group and equivalent rocks in western Saskatchewan and adjacent areas: Sask. Dept. of Min. Res. Report No. 99.

Kent, D.M., 1973, Paleozoic hydrocarbon reservoirs in Saskatchewan and their relationship to basement lineaments: Jour. Canadian Petroleum Tech., v. 12, no. 3, p. 20-24.

Kent, D.M., 1974, The relationship between hydrocarbon accumulations and basement structural elements in the northern Williston Basin. In: G.R. Parslow, ed., Fuels: A Geological Appraisal: Saskatchewan Geological Society Special Publication 2, p. 63-79.

Krumbein, W.C., and E.A. Graybill, 1965, An introduction to statistical models in geology: McGraw-Hill, New York, 475 p.

Lewry, J.F., T.I.I. Sibbald, and D.C.P. Schledewitz, 1985, Variation in character of Archean rocks in the Western Churchill Province and its significance. In: L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber, eds., Evolution of Archean Supracrustal Sequences: Geol. Assoc. Canada Special Paper 28, p. 239-261.

Petroleum Information Corporation, 1980, The Williston Basin-1980: Pub. by Petroleum Information Corporation, 305 p.

Saskatchewan Energy and Mines, 1985, Reservoir Annual 1984: Sask. Energy and Mines Misc. Report 85-1.

Sawatzky, H.B., R.G. Agarwal, and W. Wilson, 1960, Helium prospects in southwest Saskatchewan: Sask. Dept. of Min. Res. Report 49.

Sloss, L.L., and W.M. Laird, 1947, Devonian System in central and northwestern Montana: AAPG Bull., v. 31, p. 1404-1430.

Smith, D.G., and J.R. Pullen, 1967, Hummingbird structure of southeast Saskatchewan: Bull. of Canadian Petrol. Geology, v. 15, p. 468-482.

Surjik, D.L., and G.D. Hobson, 1964, An example of Prairie Evaporite mapping in the Minton area of Saskatchewan employing the seismic method: Geophysics, v. 29, p.951-956.

Swenson, R.E., 1967, Trap mechanics in Nisku Formation of northeast Montana: AAPG Bull., v. 51, p. 1948-1958.

Whitaker, S.H., J.A. Irvine, and P.L. Broughton, 1978, Coal resources of southern Saskatchewan, a model for evaluation methodology: Geological Survey of Canada Ec. Geol. Report 30.

Wilson, W., D.L. Surjik, and H.B. Sawatzky, 1963, Hydrocarbon potential of the South Regina area, Saskatchewan: Sask. Dept. of Min. Res. Report No. 76.

STRUCTURAL HISTORY OF POPLAR DOME AND THE DISSOLUTION OF CHARLES FORMATION SALT, ROOSEVELT COUNTY, MONTANA

DAVID M. ORCHARD
BHP Petroleum (Americas) Inc.
5613 DTC Parkway, Suite 600
Englewood, CO 80111

ABSTRACT

Poplar Dome, in western Roosevelt County, Montana, is a major structural feature of the western Williston Basin. Approximately 150 feet of structural closure exists at the Mississippian Ratcliffe horizon. Minor structural movement occurred in the area of Poplar Dome during Mississippian through Cretaceous time. Much of the present structural relief is the result of Laramide uplift.

Beds of salt in the Mississippian Charles Formation (Poplar interval) abruptly pinch out at Poplar Dome. Over 300 feet of salt from regionally extensive beds is missing on and near the structure. Nonsalt beds, however, extend across the dome with little thickness change and few facies changes. The stratigraphic evidence along with the presence of breccia in cores indicate that the salt beds were originally present on Poplar Dome but were subsequently dissolved. The dissolution was probably a Tertiary event caused by the introduction of fresh water along fractures induced by uplift. The removal of the salt caused a collapse over the dome which affected the structural configuration of beds younger than the Charles Formation.

In addition to the dissolution of salt beds, pore-filling salt has been dissolved from limestone of the Charles "A" and "B" units. The dissolution of this salt from Charles "A" porosity is related to the removal of bedded salt, while the flushing of salt from the Charles "B" porosity is related to a regional dissolution front encroaching from the southwest.

Poplar Dome is the site of a major oil field which has yielded more than 45 million barrels of oil, primarily from the Charles "B" porosity. The removal of pore-filling salt from the Charles "B" was a critical factor in creating this oil accumulation. The removal of salt beds also allowed the upward migration of oil into reservoirs of the Charles "A" and the Pennsylvanian Tyler Formation.

INTRODUCTION

The Poplar Dome is located in western Roosevelt County, Montana, at the eastern end of a structural trend that extends eastward along the Wolf Creek nose from Bowdoin Dome (Fig. 1). The northeast-southwest trending Brockton-Froid fault system lies to the east of Poplar Dome. Poplar Dome is a major structural feature in the Montana portion of the Williston Basin and is host to a large oil field. More than 45 million barrels of oil have been produced at Poplar Dome, primarily from reservoirs in the Mississippian Charles Formation. Unit outlines, field names, well control, and a cross-section index are shown on Figure 2. Stratigraphic terminology as used in this paper is shown on a type log in Figure 3.

Poplar Dome is shown as a closure on structure maps drawn on the base of the Upper Cretaceous Colorado Shale (Dobbin and Erdman, 1955) and the Cretaceous Greenhorn Limestone (Colton and Bateman, 1956). The discovery and development of the oil reserves has lead to structural and stratigraphic discussions by Cox (1953), Beekly (1956), Moore (1958), Brunson (1985), and Diehl (1985).

An anomalous feature of Poplar Dome is the thinning or absence of beds of halite in the Charles Formation on and near the structure. This anomaly was noted by Beekly (1956) and was briefly discussed by Cook (1976). This paper describes the manner in which the Charles salt beds pinch out at Poplar Dome. Evidence from stratigraphic relationships and core observation suggest that the absence of salt is caused by post-depositional dissolution. Related aspects of salt-plugged and salt-free porosity are of particular economic importance in the presence of reservoir-quality carbonate rock in the Charles Formation.

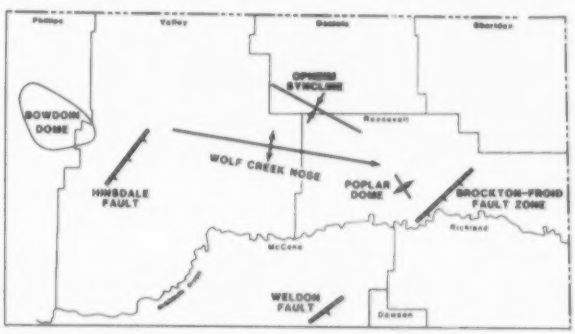


Fig. 1: Location of Poplar Dome in relation to other tectonic features of northeastern Montana.

STRUCTURE

Minor structural movements occurred along the area of the Wolf Creek Nose and Poplar Dome during the Mississippian. Northeasterly-trending anticlines were formed as shown on the Devonian Nisku to Mississippian Ratcliffe isopachous map (Fig. 4). The dome remained gently positive through the Cretaceous as shown on the Cretaceous Greenhorn to Mississippian Kibbey Limestone isopachous map (Fig. 5).

Structure on the top of the Mississippian Ratcliffe interval (base of the Green Point anhydrite) is illustrated on Figure 6. Northeasterly trending anticlines are present along the Wolf Creek Nose west of Poplar Dome, and an anticline with this trend is present at Northwest Poplar Field. The Ratcliffe structure at West Poplar Field and the East Poplar Unit is not uniformly domal but rather consists of three broad closures separated by narrow synclines. The maximum closure on the overall structure at the Ratcliffe horizon is 150 feet. The steepest dip occurs along a flexure on the northeastern and eastern sides of the dome.

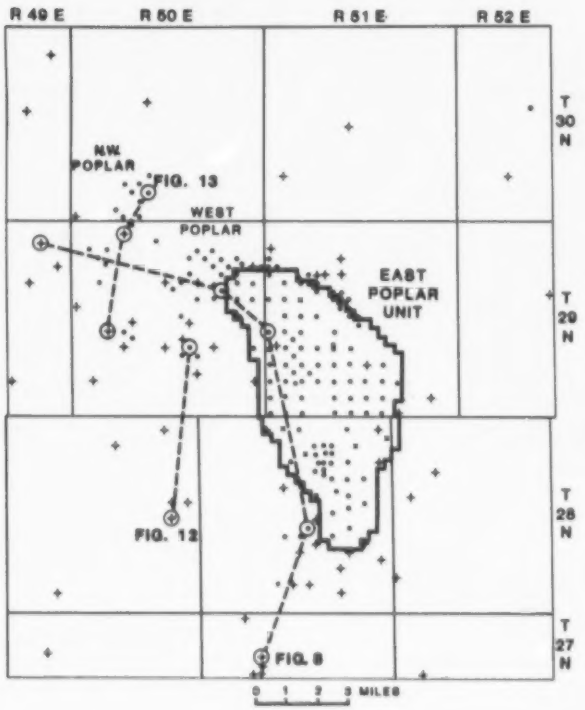


Fig. 2: Well control, unit and field locations, and cross-section index for study area.

The structure on the Mississippian Kibbey Limestone (Fig. 7) and younger horizons has a different configuration than that on the Ratcliffe. The highest parts of the structure still occur at West Poplar Field and East Poplar Unit. However,a prominent ridge is present trending northwest-southeast to the southwest of the producing areas. This ridge also appears on the Greenhorn structure map of Colton and Bateman (1956). The relationship of this ridge to the presence of salt beds in the Charles Formation is discussed later.

The major uplift leading to the present-day structural configuration occurred in post-Paleocene time. The Paleocene Fort Union Formation is eroded off Poplar Dome and the Wolf Creek nose, and the Cretaceous Fox Hills and Bearpaw Formations are exposed (Colton and Bateman, 1956). Thomas (1974) discussed the involvement of Poplar Dome and the Wolf Creek Nose in Laramide tectonics. Clement (1986) stated that the major uplift on the Cedar Creek Anticline also occurred in post-Paleocene time, with regional mid-Tertiary epeirogenic uplift.

Fracturing of Charles carbonates is described from cores by Beekly (1956) and was also observed by the present author. The configuration of the Ratcliffe structure map (Fig. 6) suggests that the broad closures may be separated by narrow grabens with faulted boundaries trending north-northeast. The overall structure trend of Poplar Dome is northwest to southeast. The influence of both northwest-southeast and northeast-southwest trends can be discerned on the isopachous map of the net Charles salt (Fig. 8).

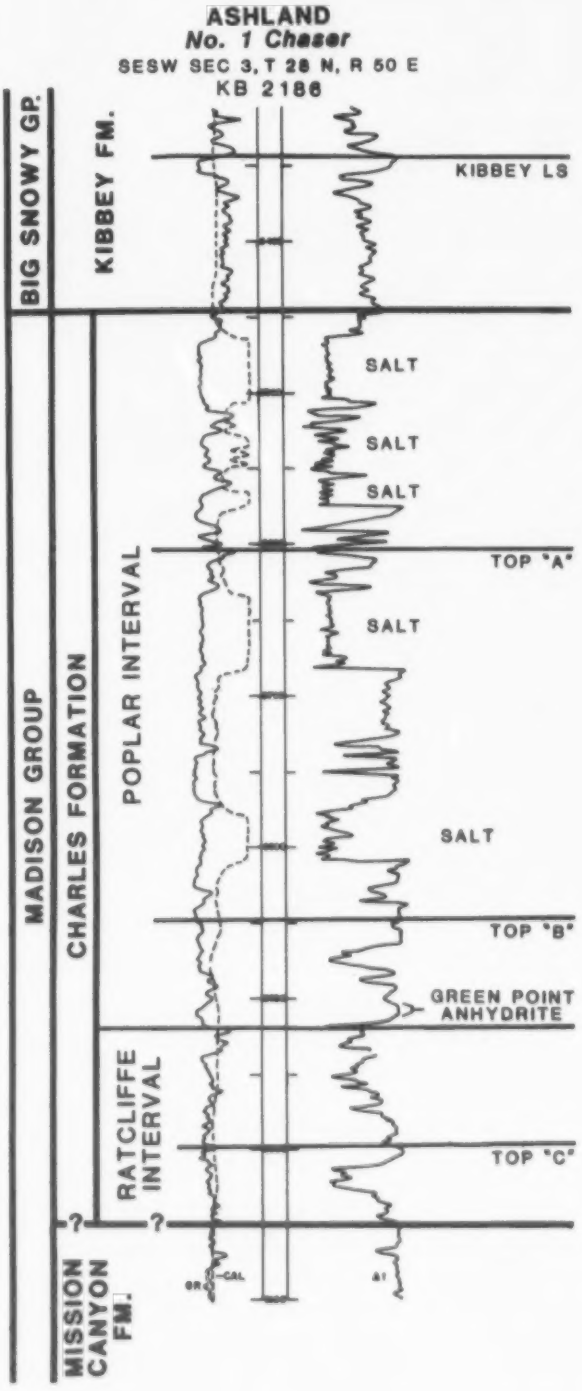


Fig. 3: Type log for Charles Formation with the stratigraphic terminology as used in this paper.

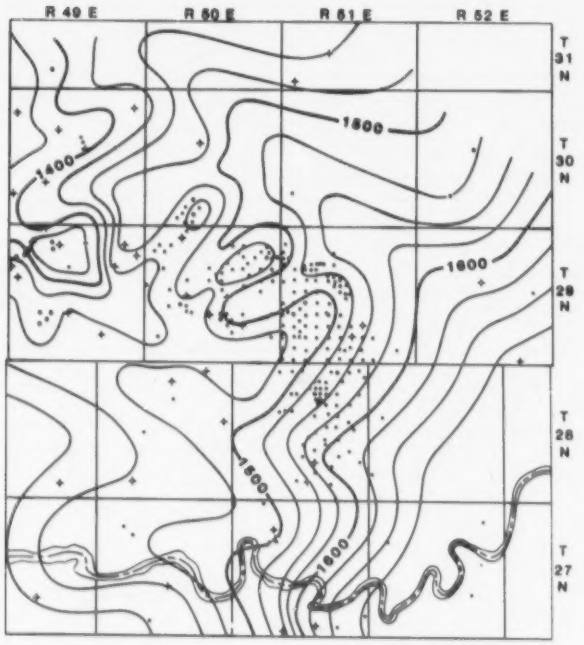


Fig. 4: Devonian Nisku to Mississippian Ratcliffe isopachous map of Poplar Dome area. Contour interval is 25 feet. Devonian penetrations shown by well symbols; shallower penetrations shown by open circles.

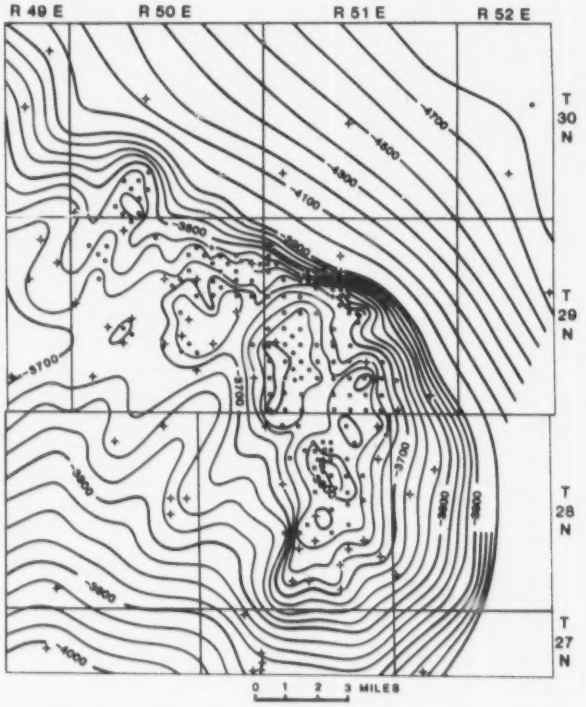


Fig. 6: Structural map of top of Ratcliffe interval, Poplar Dome area. Contour interval is 25 feet.

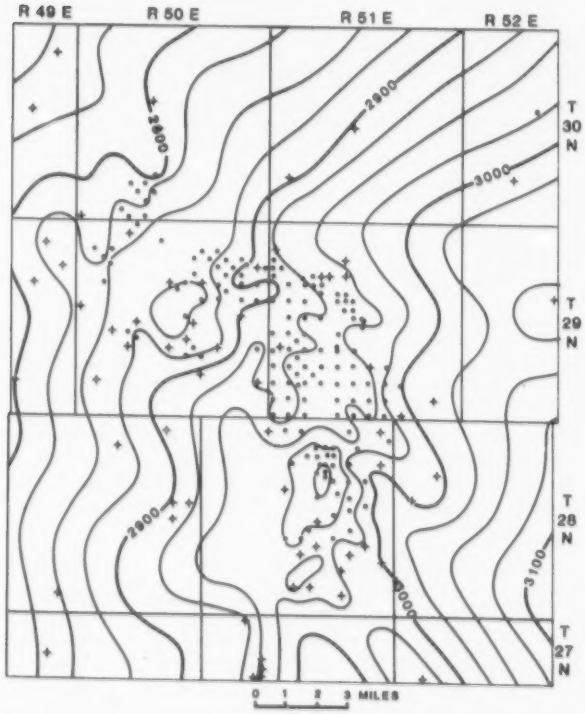


Fig. 5: Mississippian Kibbey Limestone to Cretaceous Greenhorn isopachous map of Poplar Dome area. Contour interval is 25 feet.

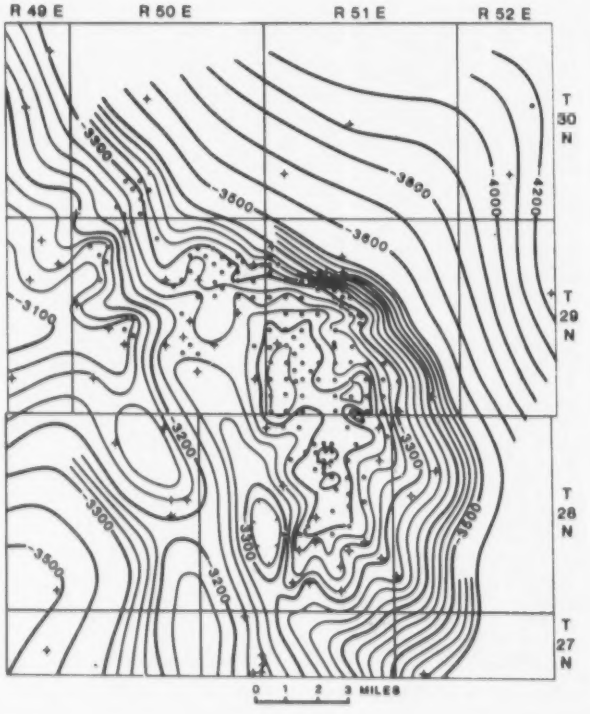


Fig. 7: Structure map on top of Mississippian Kibbey Limestone, Poplar Dome area. Contour interval is 25 feet.

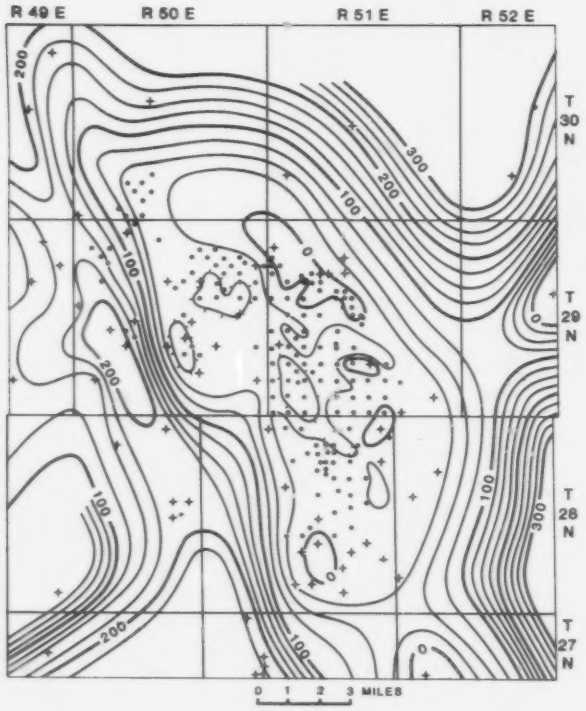


Fig.8: Isopachous map of net salt in Charles Formation, Poplar Dome area. Contour interval is 25 feet.

POPLAR INTERVAL

The Poplar interval (Carlson and Anderson, 1965; Cook, 1976) is characterized by the presence of several beds of halite separated by carbonate and anhydrite (Fig. 3). The Poplar interval overlies the Ratcliffe interval, and the contact is considered by the author to be the base of the Green Point anhydrite. This corresponds to the top of the Charles B-4 of Brunson (1985).

Individual salt beds can be traced over wide areas of the Williston Basin. The western limit of salt in the Charles is shown in Figure 9. The extent of individual salt, carbonate, and anhydrite beds in western North Dakota is presented by Cook (1976). In the vicinity of Poplar Dome, five major salt beds were deposited. The salt at 5775 feet on the type log of Figure 3 is the lowest salt deposited throughout the Poplar Dome area. A thin salt was locally deposited at the top of the Green Point anhydrite. In addition, a regionally developed salt below the Green Point anhydrite appears immediately to the east of the study area.

The reservoirs in the Charles Formation have been informally subdivided by the operators at Poplar Dome into the Charles "A," "B," and "C" zones (Beekly, 1956; Moore, 1958; Brunson, 1985). These interals are identified on Figure 3.

POPLAR INTERVAL AT POPLAR DOME

On and near Poplar Dome, many of the salt beds are missing. A map of the net Charles salt thickness (Fig.8) illustrates that the salt ranges from zero to 218 net feet. Figure 10 is a cross-section which illustrates the manner of disappearance of the salt beds onto Poplar Dome. As the dome is approached along the line of cross-section, the upper salt beds disappear first. Wells with thin salt (less than 30 feet) invariably have salt present only in the lowest salt beds. Significantly, the carbonate and anhydrite beds between the salts do not change facies or appreciably thin as the salt beds pinch out. Individual non-salt beds can be traced by log character across the structure. With neutron-density crossplots it can be demonstrated that very few lithologic changes (i.e. limestone to dolomite or carbonate to anhydrite) occur. No occurrences of non-salt to salt transition are present. Some relict insoluble sediment is present, however, at the stratigraphic position of missing salts, particularly those salts that are stratigraphically highest in the section. Units above and below a salt converge across a salt edge with no related thickness changes.

At the base of the illustration on Figure 10, values are given for net salt and net non-salt thicknesses within the Poplar interval. While the salt thickness ranges from nearly zero to over 200 net feet, the thickness of on-salt rocks varies only from 297 to 314 net feet.

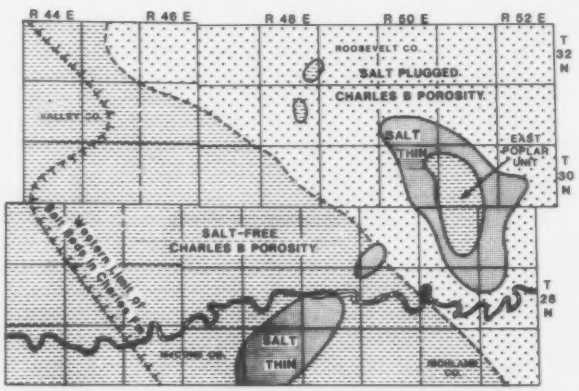


Fig.9: Regional map of salt in the Charles Formation showing western limit of bedded salt, areas of thin or absent bedded salt, and areas of salt plugging in Charles "B" porosity.

SALT DISSOLUTION

The missing salt on Poplar Dome has been previously noted in the literature. Beekly (1956) stated that the question of whether these salts were not deposited or were deposited and subsequently removed had not been resolved. Cook (1976) noted Charles salt thins over the Nesson Anticline, "Divide High," and Little Knife Anticline, and attributed these thins to syndepositional structural growth. For Poplar Dome, however, he suggested that the absence of salt beds and the lack of salt plugging in certain reservoir intervals might be the result of groundwater solution.

The question of non-deposition versus dissolution can be approached by looking at pre-Poplar interval isopachs, the character of non-salt beds across the dome, core evidence, and other instances of salt absence in the area. Non-deposition of salt on Poplar Dome would imply the presence of an underlying or syndepositional structure during Charles deposition onto which the salt beds could pinch out. Dissolution of the salt would require entry of fresh or brackfish water into the formation at some time subsequent to the deposition of the salt.

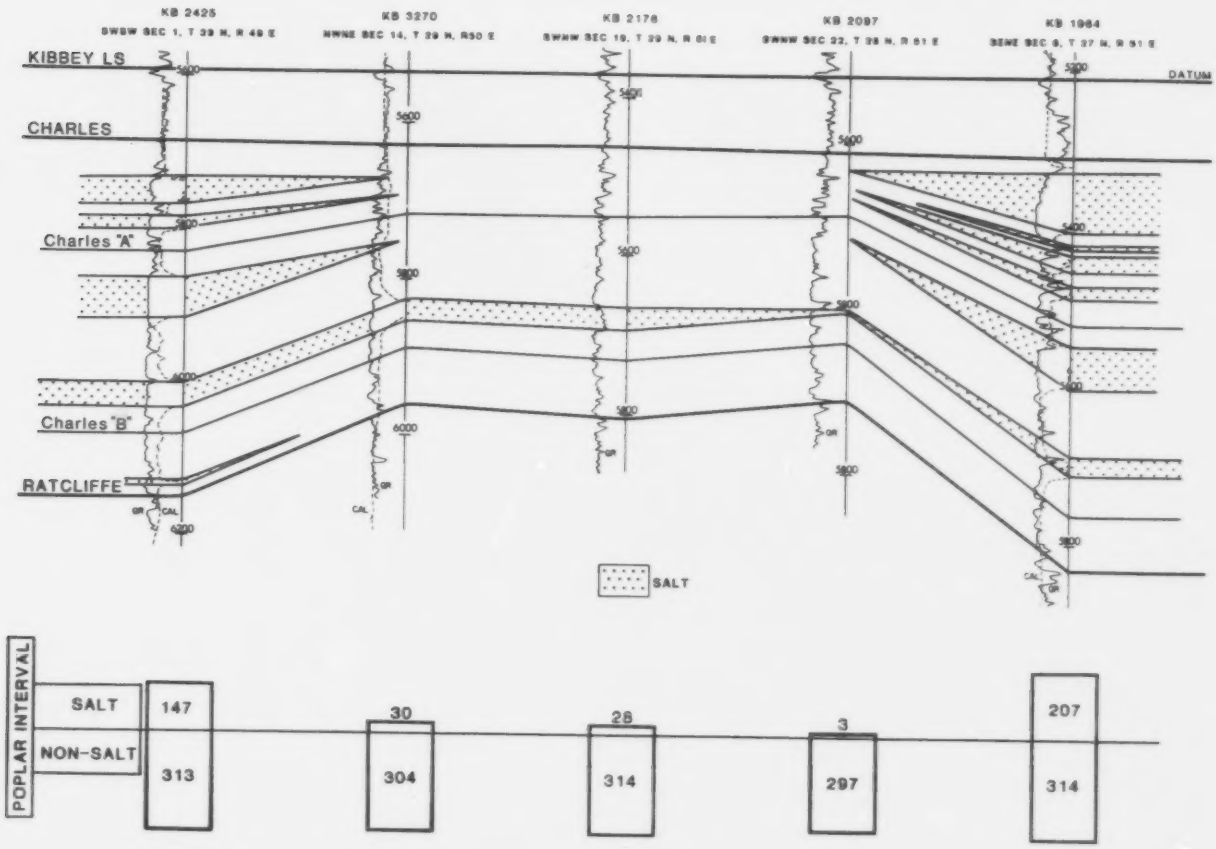


Fig. 10: Cross-section showing manner of salt pinch out onto Poplar Dome. Note the relative persistance of the lowest salt (immediately above Charles "B") and the persistence of non-salt beds. Datum is Kibbey Limestone. Values for net salt and net non-salt thicknesses in Poplar interval given at base of illustration. Locations on figure 2.

An argument against an underlying pre-existing structure can be made from the Nisku-Ratcliffe isopach (Fig. 4). On this map, the Poplar Dome is not present as a closure. Rather, northeast-southwest trending anticlines are present similar to those in the area of the Wolf Creek Nose. The magnitude and configuration of the pre-Poplar structure would not preclude deposition of salt across the dome.

Syndepositional structural growth is argued against by the character of the non-salt beds across the dome. As discussed above, these carbonate and anhydrite beds do not thin appreciably and exhibit few facies change as the salt beds pinch out. Also, the contact between the Charles and overlying Kibbey Formations is conformable, and the Kibbey Limestone to Charles interval is uniformly thick across the structure (Fig.10). To explain these features, a model of non-deposition would involve episodic uplift coincident only with periods of salt deposition and ceasing at the onset of Kibbey deposition.

Anomalously thin salt in the Charles Formation is not limited to Poplar Dome. Salt is also completely missing along the steeply dipping northeastern and eastern flanks of the structure, with the thin extending into T28-29N, R52E. Other salt thins which together form a northeast-southwest trend are present to the southwest of Poplar Dome (Fig.9).

Salt solution implies the collapse of the strata above and between the salt beds. This could lead to breccias which would be observable in cores. Most of the cores taken during the development of East Poplar Unit were through Charles "B" intervals below the lowest extensive salt bed. During a recent search, no cores could be found that sampled the exact interval from which a salt bed was missing.

A core through Charles "A" limestone at 5636-5643 feet in the Murphy #44 East Poplar Unit (SW SW Sec, 24, T28N-R51E) was examined. This section consists of dark gray lime mudstone with fractures and brecciation. Two views (horizontal and vertical faces) of a sample at 5636 feet (Fig. 11) show closely set vertical fractures and horizontal fractures and stylolites. Some of the fractures are partly or entirely healed by anhydrite. A large vug in the center of the sample is formed by the angular fit of a number of limestone fragments. This sample comes from an interval approximately 75 feet above the horizon from which 30 feet of the salt are missing. In combination with tectonic fracturing, the deformation observed in the core may be the result of the collapse of the formation when the underlying salt was dissolved.

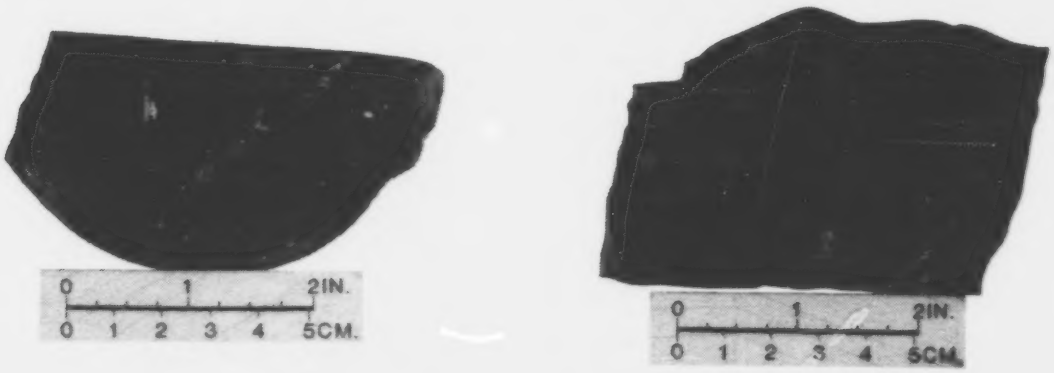


Fig. 11: Brecciated and fractured Charles "A" limestone from depth of 5636 feet in the Murphy #44 East Poplar Unit. Views of horizontal (top) and vertical (bottom) cuts through same sample.

AGE OF SALT DISSOLUTION

The age of a salt dissolution event can be recognized by identifying depositional thickening in some stratigraphic interval above the salt equal to the thickness of the missing salt. Up to 218 feet of salt is missing from the Charles Formation on Poplar Dome. No depositional compensations for this salt can be seen on the Kibbey Limestone to Greenhorn isopach (Fig. 5). From Figure 10 it can be seen that no compensation occurred in the interval between the Kibbey Limestone and the Charles Formation.

The Cretaceous Bearpaw and Fox Hills Formations are exposed at the surface at Poplar Dome, and the Paleocene Fort Union Formation has been erosionally removed (Colton and Bateman, 1956). Tertiary sediments are not present that could demonstrate depositional thickening to determine the exact time of salt removal, and that occurrence can only be stated as post-Fox Hills and probably post-Fort Union. The salt dissolution therefore appears to be a Tertiary event and may be related to fractures induced by Laramide uplift.

STRUCTURAL EFFECTS OF SALT DISSOLUTION

It was previously noted that the structural configuration on the Kibbey Limestone and other horizons above the missing salt differs from that on the Ratcliffe (below the salt). The large ridge that appears to the southwest of the dome on the horizons above the Charles is due to the preservation of salt under the ridge with removal of salt on the dome.

A comparison of two wells, Banner #1-24 Tribal (NW NW Sec. 24, T28N-R50E) and the Century #22-15 Robbins (SW SE Sec.22, T29N-R50E), illustrates the structural effect of the dissolution of the salt (Fig. 12). The salt is 163 feet thicker in the Banner well than in the Century well. At the Ratcliffe horizon, the Banner well is 103 feet low, but it is 44 feet high at the Kibbey Limestone. A 147-foot structural change has therefore occurred coincident with the removal of 163 feet of salt. The remaining 16 feet of structural difference is attributed to minor thickness variation in the non-salt beds.

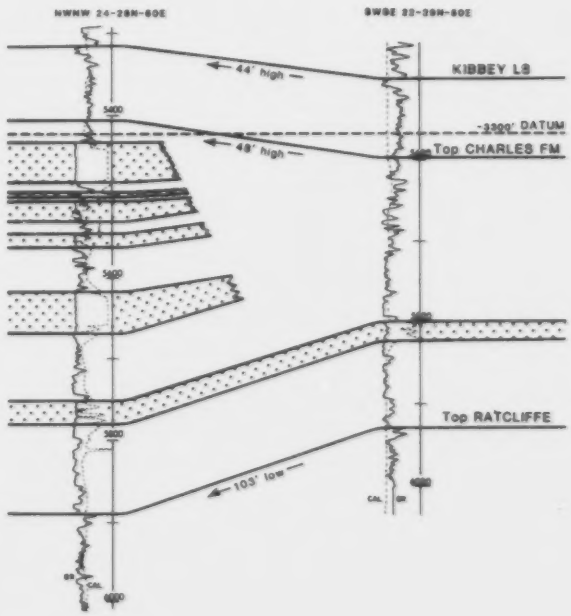


Fig. 12: Structural cross-section illustrating reversal of dip on tops of Charles Formation and Kibbey Limestone versus top of Ratcliffe interval caused by the removal of salt beds. Locations on Figure 2.

The Poplar Dome is expressed on the surface as an extension of the Wolf Creek Nose, but neither topography nor the pattern of outcropping formations clearly express domal closure (Colton and Bateman, 1956). The model of salt dissolution implies that the dome would have approximately 200 feet greater relief had the salt remained, and the surface expression of the surface would have been more pronounced.

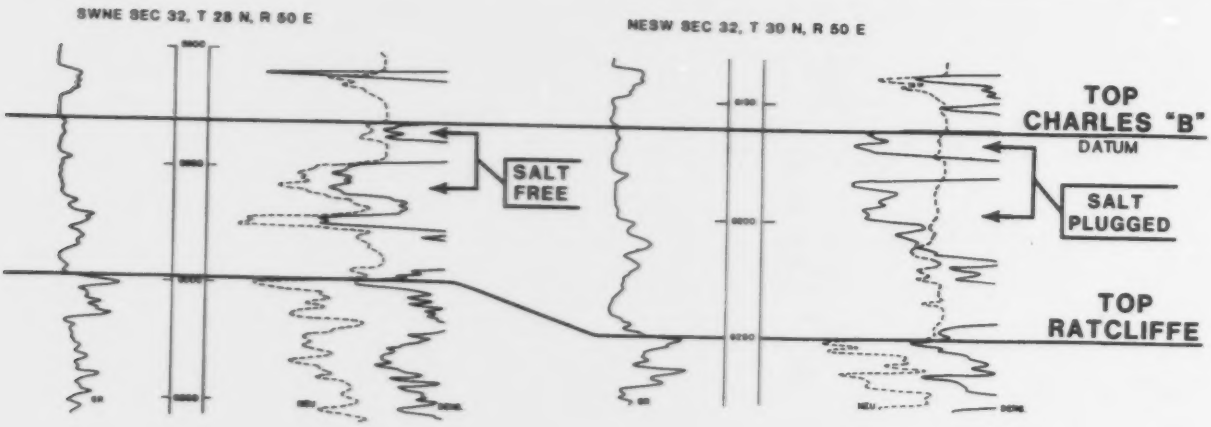


Fig.13: Comparison of neutron-density log response for salt-free and salt-plugged porosity in Charles "B" limestone.

SALT PLUGGING IN POPLAR INTERVAL RESERVOIRS

Porous zones of the Charles "A" and Charles "B" units are regionally salt-plugged but locally salt-free on Poplar Dome (Fig.9). The widespread presence of pore-plugging salt in these units in the central basin suggests that salt-plugging is the normal condition for these rocks over a wide area. The absence of salt-plugging towards the margins of that area as in the present study may be attributed to flushing.

Figure 13 compares the neutron-density log response of salt-free porous Charles "B" limestone to the same section with salt plugging. The neutron-density cross-over indicative of salt-plugging has been illustrated for other Williston Basin reservoirs by Dean (1982) and Weinzapfel and Neese (1986). Figure 14 is a cross-section showing the pattern of dissolution of the pore-plugging salt for these zones. This cross-section also reinforces the observations that the upper salt beds disappear first, the non-salt beds show continuity across the structure, and the variation is much greater for net salt than for net non-salt thicknesses within the Poplar interval (Fig. 8).

Porous zones in the Charles "A" become salt free in relation to the dissolution of stratigraphically higher salt beds. As salt beds progressively deeper in the section were removed, pore-filling salt was also flushed from porous carbonate. In Figure 14, two porous salt-free beds in the Charles "A" have lateral boundaries with salt-plugged porosity. Each of these units becomes salt-free when no bedded salt remains higher in the section.

In contrast to the Charles "A," porous Charles "B" units are variously salt-plugged or salt-free in relation to a regional boundary rather than to the dissolution of overlying salt beds. This regional boundary (Fig. 9) trends northwest to southeast, with salt-free rocks to the southwest and salt-plugged rocks to the northeast. This boundary is abrupt, with salt in equivalent beds disappearing within a lateral distance of less than one mile. Outliers of salt-free porosity to the northeast of the regional boundary are present, including a large area under the East Poplar Unit. Diehl (1985) mapped the limits of salt-plugging in Charles "B" reservoirs along the edge of the outlier through West Poplar Field. The regional salt-plugging boundary has a trend approximately parallel to the western limit of salt beds in the Charles (Fig. 9). At Poplar Dome, the area of salt-free Charles "B" porosity is coincident with, but smaller than, the area affected by dissolution of bedded salt.

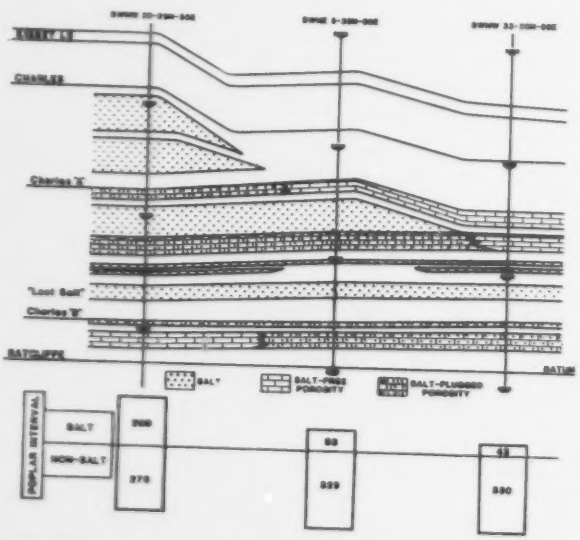


Fig. 14: Cross-section showing salt pinch outs and salt-plugged to salt-free transitions in Charles "A" and Charles "B" reservoirs. Datum is top Ratcliffe. Value for net salt and net non-salt thicknesses in Poplar interval given at base of illustration. Locations on Figure 2.

MECHANISMS OF SALT DISSOLUTION

The Madison Group is a major aquifer with hydrodynamic flow to the northeast into the Williston Basin (Feltis, 1980; Downey, 1984; Maccary, 1984). In addition, Ordovician, Pennsylvanian/Permian and Jurassic/Cretaceous aquifers flow in the same direction (Downey, 1984).

Beekly (1956) reported a chloride concentration of 182,004 ppm with sodium of 117,620 ppm for produced water at Poplar Dome. The interval from which this water was produced was not stated, but it was most probably Charles "B." Diehl (1985) provides values for total dissolved solids, at Northwest Poplar Field of 250,000 ppm for the Charles "B"

and 40,000 ppm for the Charles "C." This fresher water for the Charles "C" zone, the lowest producing zone in the Charles Formation, may be related to an influx of water in the underlying Mission Canyon Formation. Maccary (1984) mapped apparent water resistivities for the Mission Canyon and identified fresher water (higher Rwa) approaching Poplar Dome from the west.

The regional salt-plugging boundary in the Charles "B" is oriented approximately along strike with the hydrodynamic gradient for the Madison aquifer. It is probable that the salt-free porosity to the southwest of that boundary is an expression of the advancing fresh water.

Dissolution of bedded salt and salt in Charles "A" porosity appears related to water from some overlying aquifer. This is indicated by the top-down pattern of salt removal, and the relatively extensive occurrence of the lowest salt bed (5775 feet, Fig. 3) across Poplar Dome. On the net salt isopachous map (Fig. 8), northwest-southeast and northeast-southwest structural elements are expressed, suggesting that water may have been introduced into the Charles Formation along fractures which those trends.

SIGNIFICANCE OF SALT SOLUTION TO OIL PRODUCTION

The bulk of the oil produced at Poplar Dome comes from Charles "B" reservoirs. Some production has been attained from Charles "A" zones above the stratigraphic position of the lowest salt beds. Also, approximately 300,000 BO have been produced from Pennsylvanian Tyler Formation sandstones above the Charles.

Dow (1974) proposed that the Charles salt beds provide a regional seal to vertical migration of oil generated in the Bakken Formation. This model was reviewed and supported by Meissner (1978) and Webster (1984). Dow (1974) recognized that oil produced in the Tyler sandstones above Poplar Dome was Bakken oil that had been able to migrate vertically along fractures above the Charles due to the absence of salt. Other instances of upward migration cited are oil in Spearfish reservoirs in the northeastern Williston Basin and oil in Kibbey reservoirs along the Weldon Fault. The current work would add Charles "A" reservoirs to the Tyler as being charged by vertical migration through the areas where salt is totally absent.

From the regional distribution of salt-plugged porosity in the Charles "B" reservoirs (Fig. 9), it appears that the major reservoirs at Poplar Dome were originally plugged. The removal of this salt is a major factor in the creation of the large oil field at Poplar Dome. In addition, removal of pore-filling salt from Charles "A" reservoirs has allowed a small amount of production from those zones.

ACKNOWLEDGEMENTS

This paper is presented with the permission of BHP Petroleum (Americas) Inc., and the author is grateful for that permission and support. The manuscript was critically reviewed by Nels E. Voldseth, Jeffrey M. Dunleavy, Robert G. Lindsay, and Suzanne E. Reeves. The illustrations were prepared by Barry Perow, and the manuscript was typed by Kathryn Portus.

REFERENCES CITED

Beekly, E.K., 1956, Poplar-type field, Montana: North Dakota Geol. Soc. and Saskatchewan Geol. Soc.: First International Williston Basin Symposium, pp. 61-65.

Brunson, T., 1985, Poplar east field In: Montana Oil and Gas Fields Symposium, Montana Geol. Soc., Billings.

Carlson, C.G. and Anderson, S.B., 1965, Sedimentary and tectonic history of North Dakota part of Williston Basin: AAPG Bull., Vol. 49, No. 11, pp. 1833-1846.

Clement, J.H., 1986, Cedar Creek: a significant paleotectonic feature of the Williston Basin; In: Peterson, J.A., ed., Paleotectonics and Sedimentation in the Rocky Mountain Region, United States: AAPG Mem. 41, pp. 213-240.

Colton, R.B., and Bateman, A.F., Jr., 1956, Geologic and structure contour map of the Fort Peck Indian Reservation and vicinity, Montana, USGS Misc. Geol. Invest. Map I-225.

Cook, C.W., 1976, A mechanical well log study of the Poplar interval of the Mississippian Madison Formation in North Dakota; North Dakota Geol. Surv. Rept. of Invest. #52, 20 pp.

Cox, H.M., 1953, Williston Basin - Mississippian reservoir characteristics and proved reserves: AAPG Bull., Vol. 37, No. 10, pp. 2294-2302.

Dean, K., 1982, Devonian Dawson Bay Formation in northwestern North Dakota: Fourth International Williston Basin Symposium, Saskatchewan Geol. Soc. and North Dakota Geol. Soc., pp. 89-92.

Diehl, L.A., 1985, Poplar Northwest Field; In: Montana Oil and Gas Fields Symposium, Montana Geol. Soc., Billings.

Dobbin, C.E., and Erdman, C.E., 1955, Structure contour map of the Montana plains: USGS Oil and Gas Inv. Map #OM-178A.

Dow, W.G., 1974, Application of oil-correlation and source-rock data to exploration in the Williston Basin: AAPG Bull., Vol. 58, No. 7, pp. 1253-1262.

Downey, J.S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: USGS Prof. Paper #1273-G.

Feltis, R.D., 1980, Potentiometric surface map of water in the Madison Group, Montana: Montana Bur. Mines and Geol., Hydrogeologic Map #2.

Jensen, F.S., and Varnes, H.D., 1964, Geology of the Fort Peck area, Garfield, McCone,and Valley Counties, Montana: USGS Prof. Paper #414-F, 49 pp.

Maccary, L.M., 1984, Apparent water resistivity, porosity, and water temperature of the Madison Limestone and underlying rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: USGS Prof. Paper #1273-D.

Meissner, F.F., 1978, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana, In: Montana Geol. Soc., Williston Basin Symposium: Billing, pp. 207-230.

Moore, W.J., 1958, Poplar field east, In: Nordquist, J.W. and Johnson, M.C., eds., Montana Oil and Gas Fields Symposium (revised): Billings Geol. Soc., pp. 196-197.

Thomas, G.E., 1974, Lineament-block tectonics, Williston-Blood Creek Basin: AAPG Bull., Vol. 58, No. 7, pp. 1305-1322.

Webster, R.L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation; In: Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mtn. Assoc. of Geol., pp. 57-81.

Weinzapfel, A.C., and Neese, D.G., 1986, Gooseneck Field, northern Williston Basin; In: Rocky Mountain Oil and Gas Fields, Wyoming Geol. Soc., pp. 61-82.

TABLELAND PHOTOLINEAMENT PATTERN REVISITED

J.D. MOLLARD

J.D. Mollard and Associates Limited
510 Avord Tower - 2002 Victoria Avenue
Regina, Saskatchewan, Canada
S4P 0R7

ABSTRACT

Distinctive lineament- and ring-patterns appear in airphotos of the landscape surrounding Home Oil's February 1986 deep oil discovery near the abandoned CPR siding of Tableland, Saskatchewan. I identified the photolineament patterns and reported it in the petroleum literature over 30 years ago. In a paper presented in 1959 at the Second Williston Basin Symposium in Regina, I suggested that this remarkable pattern might reflect some type of basement structure such as a hinge line, the effect of which has been perpetuated upward into the overlying sedimentary strata. Because the area is being actively explored for major oil reservoirs in the Devonian Winnipegosis Formation, implications of the remotely sensed photolineament- and ring-patterns in petroleum exploration have taken on added significance. As a consequence, remotely sensed surface features and subsurface geological, hydrogeological, and seismic trend data are currently being synthesized and correlated. These data include near-surface preglacial, glacial and postglacial features and events that appear to be affected by deeper structure in the subsurface.

Lineament block tectonics may have influenced geological events, including shoaling and reefing in the Devonian Winnipegosis, salt removal in the overlying Prairie Evaporite, and differential subsidence that has continued to the present. These interrelated geological events are thought to be responsible for the anomalous surficial lineament- and ring-patterns in the area around the Home Oil discovery well, and for their apparent areal association with reefs in the Winnipegosis Formation lying about 2650 m below ground surface.

INTRODUCTION

The main purposes of this paper are to discuss the origin of remotely sensed surface patterns at Tableland, Saskatchewan, and to assess their significance in the search for Devonian reservoirs. Surface expressions of remotely sensed photolineament- and ring-features are presented, and correlations with surface and subsurface geological data are made. A proposed genetic model, implications of that model for deep oil exploration in the Devonian, and planned future studies are presented.

In the late 1950s, regional photolineament studies were performed for companies exploring for oil in southern Saskatchewan (Mollard 1957a, b, 1958, 1959). By far the most remarkable photolineament pattern identified during those studies (Fig. 1) was observed in the area of Home Oil's 1986 major deep discovery in the Devonian Winnipegosis Formation. The area is located near the abandoned siding of Tableland on the Canadian Pacific Railway in T2-R9W2M, approximately 10 km west of Estevan, Saskatchewan. Photolineaments appear as subparallel alignments in the microrelief and drainage, and in airphoto tones that reflect minor changes in soil moisture and plant growth. These microfeatures are extremely difficult to identify in the field.

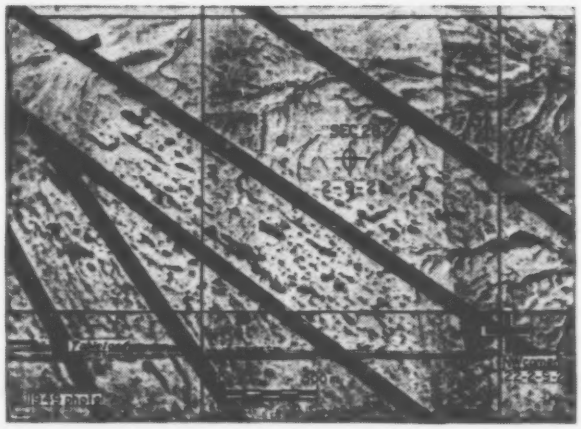


Fig. 1 Part of a 1949 airphoto showing a sharp break between strong N35°W and N55° lineament sets northeast of the abandoned Tableland siding, west of Estevan, Saskatchewan. Black cross shows the location targeted for oil exploration in the late 1950s (Mollard, 1957a, 1958, 1959).

Several surface and near surface geological and hydrogeological studies have been carried out in the Estevan area since the original photolineament studies were made in the 1950s. These include groundwater exploration along major preglacial valleys and their larger tributaries, dam-site and reservoir studies for the Rafferty Dam project, site-selection studies for a proposed thermal power plant near Estevan, and sand and gravel searches for contractors in the Estevan area. During these studies, I re-examined the Tableland photolineament pattern several times.

Because the Tableland area was targeted for petroleum exploration 19 years before Dome-Scurry Rainbow drilled a deep wildcat well in LSD 11-14-2-9-W2M in November 1975, and 30 years before Home Oil followed with a major deep oil discovery in LSD 8-22-2-9-W2M in February 1986, this update of accessible data is appropriate.

SURFACE EXPRESSIONS OF THE TABLELAND PHOTOLINEAMENT- AND RING-PATTERNS

PHOTOLINEAMENT PATTERN AT TABLELAND

Certain features of the photolineament pattern at Tableland show up better in the older and larger scale airphotos taken in 1937 and 1949 (Fig. 1). However, a better regional appreciation of the lineament sets is observed in the smaller scale airphotos taken in 1970 and 1979 — especially after the surficial lineaments are enhanced xerographically. Lineaments plotted from the 1970 airphotos (Fig. 2) show dominant trends in the region of Tableland, with a change in direction passing through a bullseye pattern near the northwest corner of Section 14-2-9-W2M. A rose diagram of 350 photolineaments (Fig. 3a) mapped in the area around the Home Oil wells in LSDs 8 and 9-22-2-9-W2M reveals the number of trends that

can be identified on xerographic copies of 1:80,000 scale airphotos. Several of these trends also show up on rose diagrams of till joints (Fig. 3b) mapped in the field. The techniques used to collect and analyze data on joint fractures in Saskatchewan tills are given in a paper by Penner and Reeves (1986).

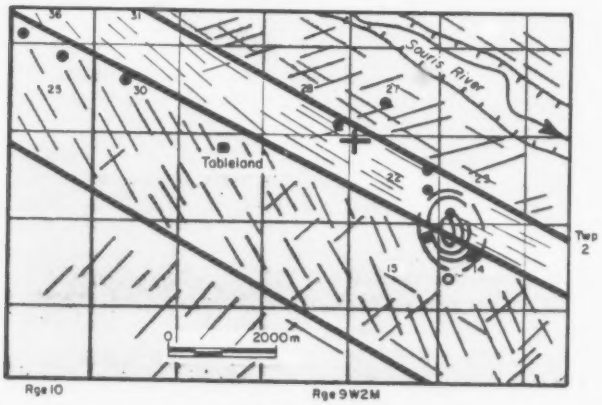


Fig. 2 Prominent photolineaments interpreted from 1979 airphoto A25195-135. The white band follows the white inferred Tableland lineament trend. Note the bullseye feature centrally situated between several oilwells. Black dots are recent exploration holes or completed oilwells in the Devonian Winnipegosis Formation. Black cross from 1950 photolineament studies (Mollard, 1957a, 1958, 1959).

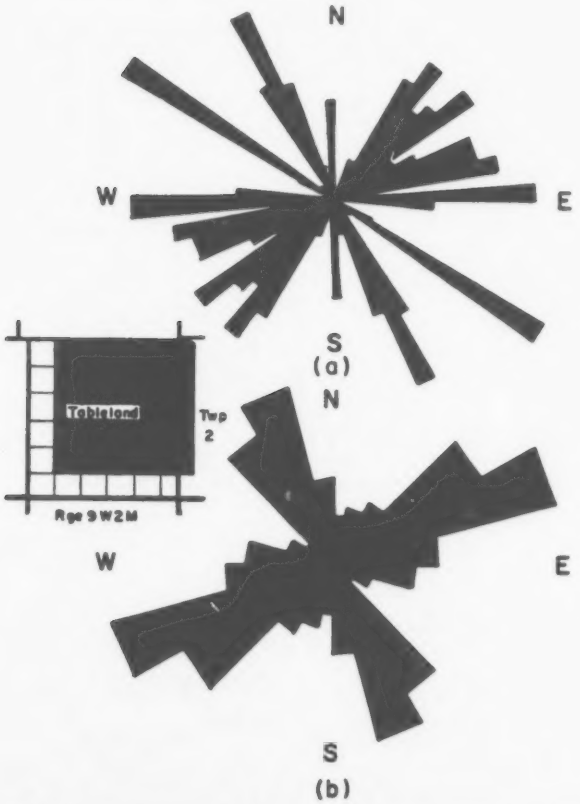


Fig 3. (a) Rose diagram summarizing orientations of 350 photolineaments in 90 km² in the Tableland deep oil exploration area (see inset); photolineaments interpreted from enhanced airphoto A21739-81. (b) Rose diagram summarizing orientations of 150 field-mapped joints in till in the side of a backhoed testpit in LSD 6-15-2-9-W2M. Note that certain trends in (a) also appear in (b).

Four pervasive trends in the region around Tableland were identified on 1979 photos: N45 to 60°W, N30 to 45°W, N30 to 45°E, and N45 to 60°E (Fig. 4). These trends match regional lineament and subsurface fracture trends identified in southeastern Saskatchewan, northeastern Montana, and northwestern North Dakota (Table 1). Two of the strongest regional lineament trends mapped in the 1950s also tend to match alignments of oil and gas pools in southeastern Saskatchewan (Fig. 5).

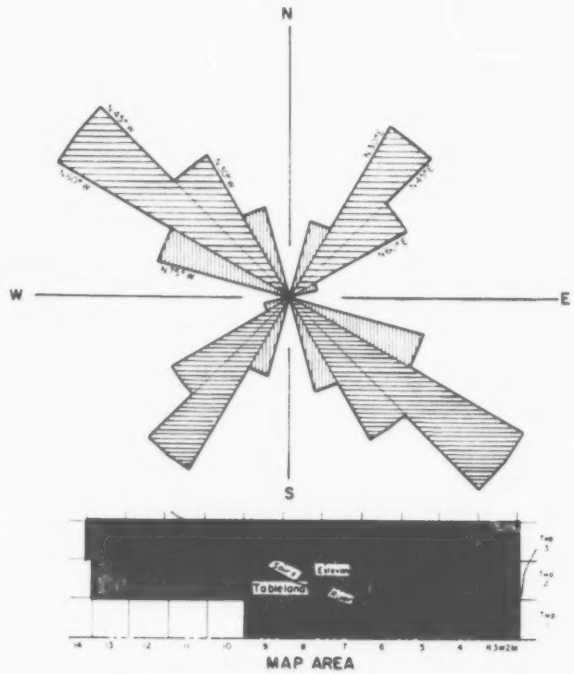


Fig. 4 Dominant regional photolineament trends in 2800 km² area centred around Estevan, Saskatchewan (see inset). Lineaments were identified from 1:80,000 airphotos taken in 1970.

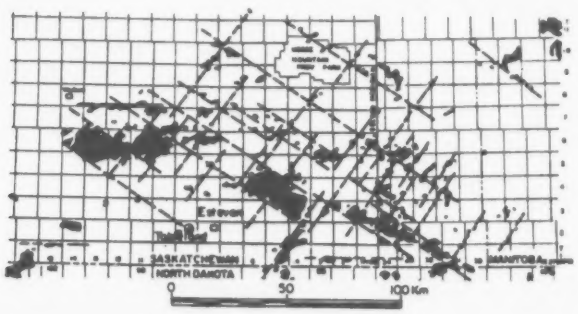


Fig. 5 Suborthogonal northwesterly and northeasterly dashed lines represent two preferred photolineament trends mapped in southeastern Saskatchewan in the late 1950s (Mollard, 1958). Solid black areas are oil and gas pools in southeastern Saskatchewan (from Williston Basin Map showing oil and gas pools prepared by Terra Graphics, Denver, Colorado, 1978).

Regional surficial lineaments oriented N45 to 60°W and N30 to 45°E trend in much the same directions as the continental arches that enclose sedimentary basins, such as the Williston Basin (Sanford et al, 1985), regional salt solution edges (Worsley and Fuzesy, 1979), pervasive alignments in the drainage (Mollard, 1958), trends on the potentiometric surface map of the Mannville Group (Christopher, 1980), and paleo-

Table 1. Regional and local dominant linear trends of surface and subsurface geological features in southeastern Saskatchewan and adjoining areas.

Lineament trend type	Preferred orientations	Source of information
Suborthogonal trends surrounding the Williston Basin	N50-55°W N35-40°E	Sanford et al., 1985
Major lineaments and crustal fractures in Williston Basin area	N50-55°W & N35-40°E	Siegel and Gillespie, 1980
Regional lineament trends in northeastern Montana and northwestern North Dakota	N55°W & N55°E	Thomas, 1974
Dominant trends of beds on Mississippian subcrop map T 1 to 6, R 30 WPM to R 4 W2M	N55-60°W & N35-40°E	Fuzesy et al., 1976
Preferred trends on 1978 oil and gas pool map of southeastern Saskatchewan	N55-60°W & N35-40°E	Terra Graphics, Denver, 1978
Structure map on the top of the Souris River Formation	N35-50°E & N40°W	Lane, 1985
The Elbow-Weyburn lineament	N55°W	Christopher, 1980
The Brocton-Froid lineament	N55°E	Gerhard, 1986
The Goose Lake trend	N45°W	Gerhard, 1986
Trends on earthquake map of southeastern Saskatchewan adjoining Montana and North Dakota	N45-55°W & N50-55°E	Pacific Geoscience Centre map, 1986
Peak regional fracture directions, drainage and topographic lineaments	N40°W & N50°E	Stauffer & Gendzwill, 1986 (in press)
Inferred trend of maximum principal horizontal compressive stress trajectory, S_{Hmax}	N50-55°E	Stauffer and Gendzwill, 1986 (in press)
Solution edge of Prairie Evaporite Formation near Lake Alma	N55°E	Wilson, et al., 1963
Controlling lineaments suggested by salt solution features and outlines of potash members	N55°E & N35-45°W	Worsley and Fuzesy, 1979
Oil poll trends, Lake Alma area	N50-55°E & N55-60°W	Kent, 1973 and Terra Graphics, Denver, 1978
Lineament connecting oil pools on regional seismic map, Lake Alma area, southeastern Saskatchewan	N55°W	Kent, 1973
Surface lineaments near Lake Alma	N55°W; N55°E; N35°E; N75°E	This study
Dominant regional photolineament trends	N50-60°W & N35-40°E N35-40°W & N50-55°E	Hollard, 1957,1958,1959
Tableland photolineament	N55°W	Hollard, 1957,1958,1959
General trends on potentiometric map of Mannville formation water in southeastern Saskatchewan	N50°-55°W & N50-55°E	Christopher, 1980
Surface lineaments near Tableland	N30°W; N55°W; N35°E; N75°E	This study
Rectangular outline of Boundary Dam reservoir	N40°E; N50°W	This study
Locally thick trends on the isopach map of the Boundary coal seam west of Estevan	N40°W	Irvine et al., 1978; this study
Souris River valley west of Tableland	N55°W	This study
Paleo-structural lineations in southeastern Montana and adjoining area	N30-45°W & N45-60°E	Brown, 1978

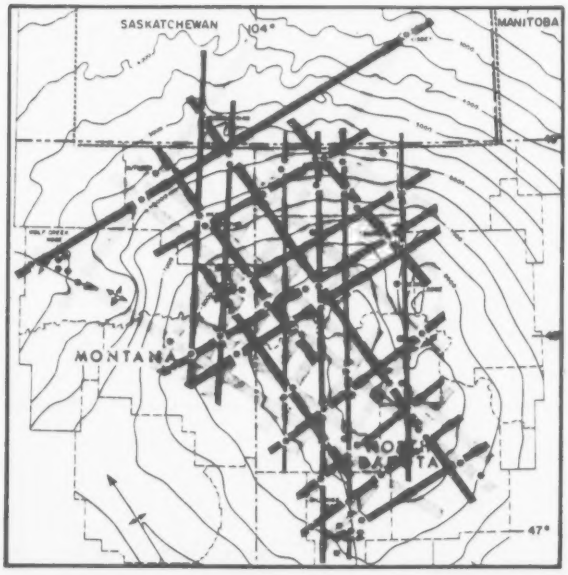


Fig. 6 Five dominant regional photolineament trends appearing in Figure 3(a) superimposed on a map of aligned Devonian reservoirs located in northeastern Montana and northwestern North Dakota (map showing Devonian reservoirs by Kissling and Ehrets, 1986). Note that Devonian reservoirs appear to be located at the intersections of different sets.

and modern valleys in southeastern Saskatchewan (Van der Kamp et al, 1986).

Lineament peaks on Figure 3 occur at N55°W, N35°W, N35°E, N55°E, N-S, E-W and N75°E. If the N55°W, N35°W, N-S, N35°E and N55°E bearings are overlain on a plot of Devonian reservoirs in northeastern Montana and northwestern North Dakota (Kissling and Eherts, 1986), nearly all of the Devonian reservoirs coincide with lineament intersections (Fig. 6). A similar finding has been observed in southwestern Ontario (Sanford et al, 1985). This raises the question as to whether or not the Devonian reservoirs and regional lineament intersections are genetically related.

In about the last 15 years, several authors have presented data on regional lineament- and fracture-patterns in the Williston Basin (Erickson, 1970; Kent, 1973, 1974, 1984; Thomas, 1974; Shurr, 1978; Brown, 1978; Worsley and Fuzesy, 1979; Christopher, 1980; Siegal and Gillespie, 1980; Sanford et al, 1985; Gerhard, 1986; Stauffer and Gendzwill, 1987). A compilation of dominant lineament trends reported in the literature suggests the trends to be fairly consistently oriented over large areas (Table 1).

RING FEATURES AT TABLELAND

Ovoid and subcircular features occur in the photolineament pattern of the area surrounding the Dome-Scurry Rainbow, Home Oil, and Canadian Hunter oilwells. The most remarkable of these are crudely concentric dark-toned arcs forming a bullseye pattern (Fig. 2). This feature may have resulted from differential salt dissolution, compaction, and/or draping of highs deep in the subsurface. Other arcs, which may be segments of incompletely developed rings, can also be seen in the Tableland area (Figure 7a). Whether or not the inferred highs at depth are basement hills, large Winnipegosis mounds, or smaller pinnacle reefs on Winnipegosis mounds, is unknown. A small annular feature at LSD 16-15-2-9-W2M (Fig. 7a, b), where an oilwell into the Winnipegosis was recently completed, may be mere coincidence. However, strength is gained for a genetic connection with Winnipegosis reefs when one considers that the present bevelled surface at Tableland resulted from extensive early postglacial sheet erosion caused by a catastrophic flood (Kehew,1982).

CORRELATION OF THE REMOTELY SENSED LINEAMENT- AND RING-PATTERNS WITH GEOLOGICAL DATA

INFERRED BASEMENT CONTROL AND SALT-DISSOLUTION EFFECTS

Several authors have suggested that tectonism has influenced the propagation and perpetuation of lineaments and their association with hydrocarbon reservoirs (Kent, 1973, 1974, 1984; Thomas, 1974; Brown, 1978; Shurr, 1978; Slack, 1981; Gerhard, 1986; McCoy et al, 1986; Merin and Moore, 1986; Michael and Merin, 1986). Moreover, zones of weakness and movement along basement lineaments in the Williston Basin of southeastern Saskatchewan are thought to have governed salt removal from the Devonian Prairie Evaporite (Wilson et al, 1963; Holter, 1969; Kent, 1974; Worsley and Fuzesy, 1979). Worsley and Fuzesy (1979) note that linearity and angularity are suggestive of control along basement block lineaments, and that this effect may be observed along the salt edge flanking the Hummingbird trough. This observation, and the work of Wilson et al (1963) and Holter (1969), inspired the effort to correlate lineaments identified on remotely sensed imagery with salt-dissolution features in the Hummingbird trough area near Lake Alma, Saskatchewan. Such a correlation, it was thought, might help explain the origin and surface

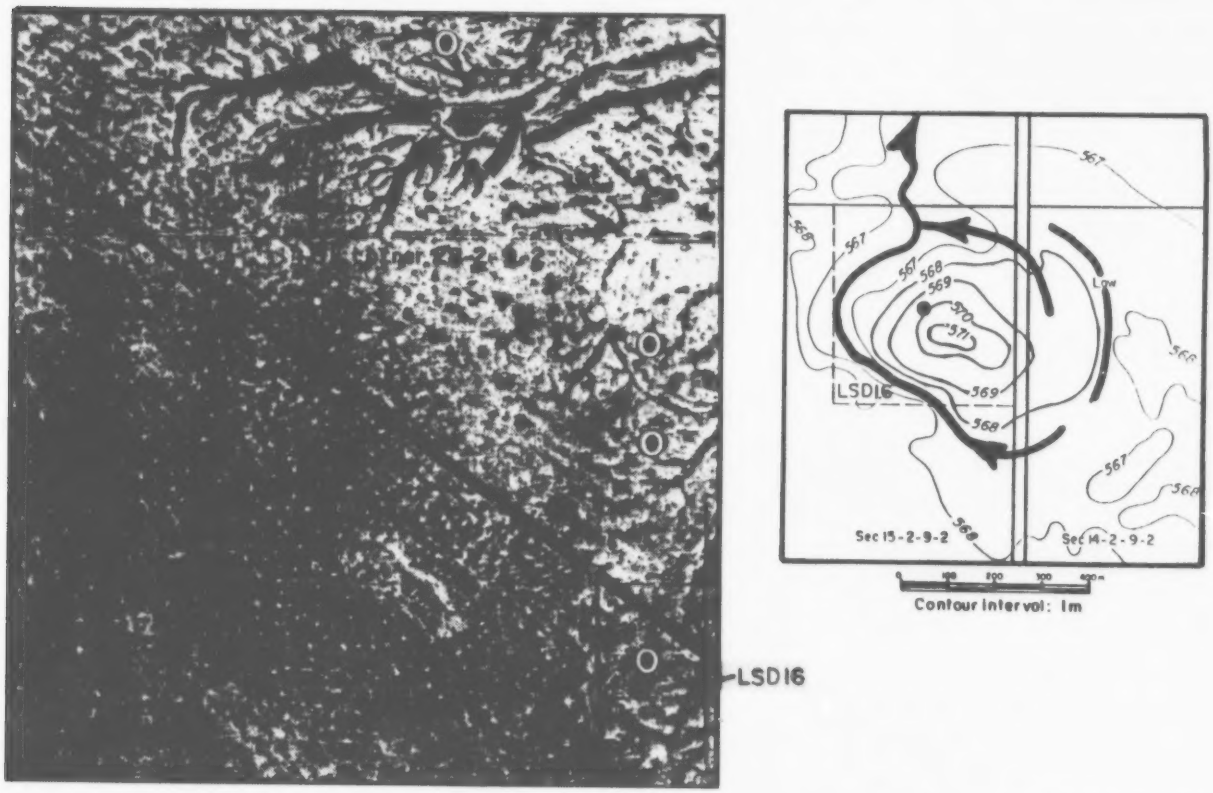


Fig. 7 (a) Airphoto showing subannular ring and curving arc features (black arrows) in the relief and drainage. Note especially the annular feature in LSD 16-15-2-9-W2M. Black dots are deep exploration holes and completed oil wells in the Devonian Winnipegosis Formation. (b) A detailed topographic map (contour interval: 1 m) of the subannular feature appearing in LSD 16-15-2-9-W2M.

Fig. 8 Airphoto showing an anomalous change in direction of linear crevasse fillings and aligned kettleholes in stagnation moraine, west of Lake Alma, Saskatchewan. The line of intersection separating dominant trends matches closely the location and trend of the Prairie Evaporite salt edge at a depth of about 2.7 km (see Fig. 9).

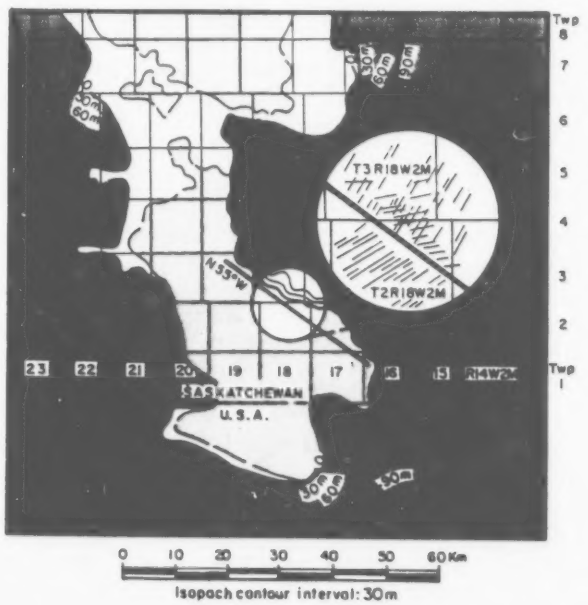
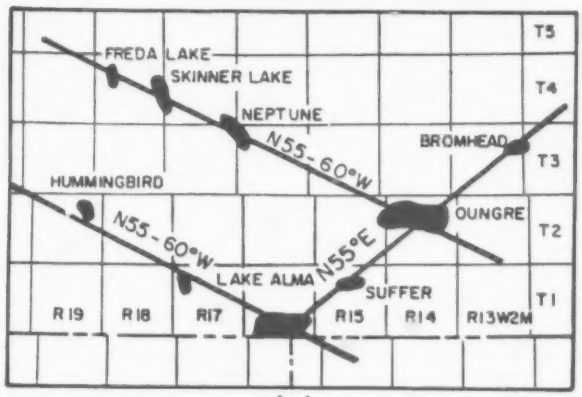
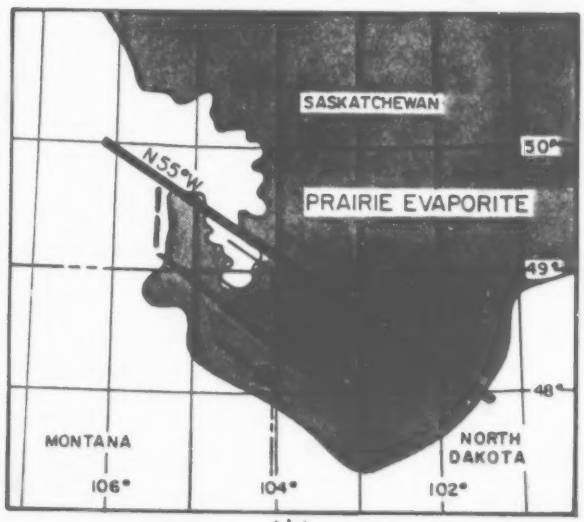


Fig. 9 Isopach map of Devonian Prairie Evaporite Formation in the Hummingbird trough area. The inset shows the trends of linear glacier disintegration features interpreted from Figure 8. Light grey shows the Mississippian-Jurassic solution area, white the Cretaceous-Recent solution area, and dark grey the present salt area. Location: Lake Alma area, south-central Saskatchewan.



(a)



(b)

Fig. 10 (a) Succession of oil pools aligned N55-60°W and N55°E in the Lake Alma area, south-central Saskatchewan. (b) Arrows show trend of anticlinal noses in Devonian, Silurian, and Ordovician strata. Dashed lines show N-S and NW-SE trends of basement gravity highs (from Kent, 1973).

expression of the extraordinary photolineament and ring patterns observed around Tableland.

The orientation of linear ice-disintegration features was found to change abruptly above the Hummingbird trough salt edge west of Lake Alma (Figs. 8 and 10). This change is similar to that observed at Tableland (Fig. 2), thereby suggesting that salt dissolution is a factor in creating Tableland's anomalous pattern.

Wilson et al (1963) and Kent (1974) suggest that basement features have influenced the occurrence of petroleum reservoirs, anticlinal structures, and basement gravity trends in the Lake Alma area of south-central Saskatchewan (Fig. 10a, b). Paleotectonic control may also be inferred from the irregular profile of stratigraphic contacts evident along a 2650 m thick section through the Williston Basin (Wright and Kent, 1984). The stratigraphic section for the area around the Hummingbird trough indicates extensive collapse features (Fig. 11).

In addition, earthquake epicentre alignments, possibly associated with periodic movements along Precambrian faults and block boundaries, have preferential NW, NE and NS trends (Fig. 12). Typically, large basement block boundaries are the loci of recurring earthquakes (Gallager, 1981).

SURFACE GEOLOGY

Crisscrossing negative (microdepressional) lineament- and ring-structures cannot be explained easily by glacier deposition because they appear on a postglacial stream-eroded surface. Following the retreat of glacier ice, meltwaters stored in proglacial Lake Regina spilled down the Souris River valley (Christiansen, 1956; Kehew, 1982). This spillway was about 7 km wide at Tableland, and straddled the present Souris River valley. The surface expression of the Tableland lineament- and ring-patterns are best developed on the stream-bevelled Souris Spillway floor (Fig. 2).

During the drainage of glacial Lake Regina, the ancestral Souris River removed a surface layer of glacial sediment and, in the process, produced a series of lemniscate-shaped erosional remnants called residuals (Kehew and Lord, 1986). Curving scarps around the residuals match the local direction of meltwater flow, and, rarely, the direction of the strong lineament sets. In fact, individual lineaments disappear at the curving base of some erosion residuals. This would indicate that meltwater flow is not the only factor that accentuated the photolineament pattern at Tableland.

A pronounced northwest-trending lineament set roughly parallels both the inferred direction of the last iceflow (Christiansen, 1956) and the trend of the Souris River valley. However, other well expressed lineament sets trend at large angles to the directions of glacier ice and meltwater flow neither of which could therefore have been genetically responsible for these other lineament sets (Figs. 2 and 3). Consequently, basement structure becomes a likely causative factor through fracturing of the overlying sedimentary rocks. Apparently these fractures affected salt removal and differential subsidence, creating further fracture propagation and reinforcement of the lineament pattern.

The possibility of multidirectional glacier flow and fluting and a resulting multidirectional clast fabric in the drift at Tableland have been considered (Mollard, 1984). Systematic fractures formed in disintegrating stagnant ice may produce linear crevasse fillings and aligned kettlehole depressions, as evidenced near Lake Alma (Fig. 8). However, at Tableland, such linear ice features would probably have been erased by postglacial stream erosion of the Souris Spillway floor.

FLUVIAL MORPHOLOGY AND ACTIVE TECTONICS

Locally, the modern Souris River valley is aligned along the direction of glacier flow as well as the extension of a strong N55°W trending lineament at Tableland. To determine whether or not significant changes related to tectonism could be detected in river sinuousity and valley bottom gradient, a detailed longitudinal profile along the Souris floodplain west of Tableland was plotted and studied (Fig. 13). Interestingly, marked changes appear as distinct breaks in sinousity (the ratio of channel length to valley length) along the valley bottom at B and C in Figure 13. Also, the valley floor gradient is much steeper along reach BC than along reaches AB and CD, which have similar gradients and the Souris River channel is much straighter along AB than BC. The reason for these differences is probably long-term tectonism or differential rebound following glacier melting.

Valley floor and longitudinal river profiles are known to be sensitive indicators of tectonism (Bendefy et al, 1967; Zuchiewicz, 1979; Schumm, 1986). To maintain a constant gradient,

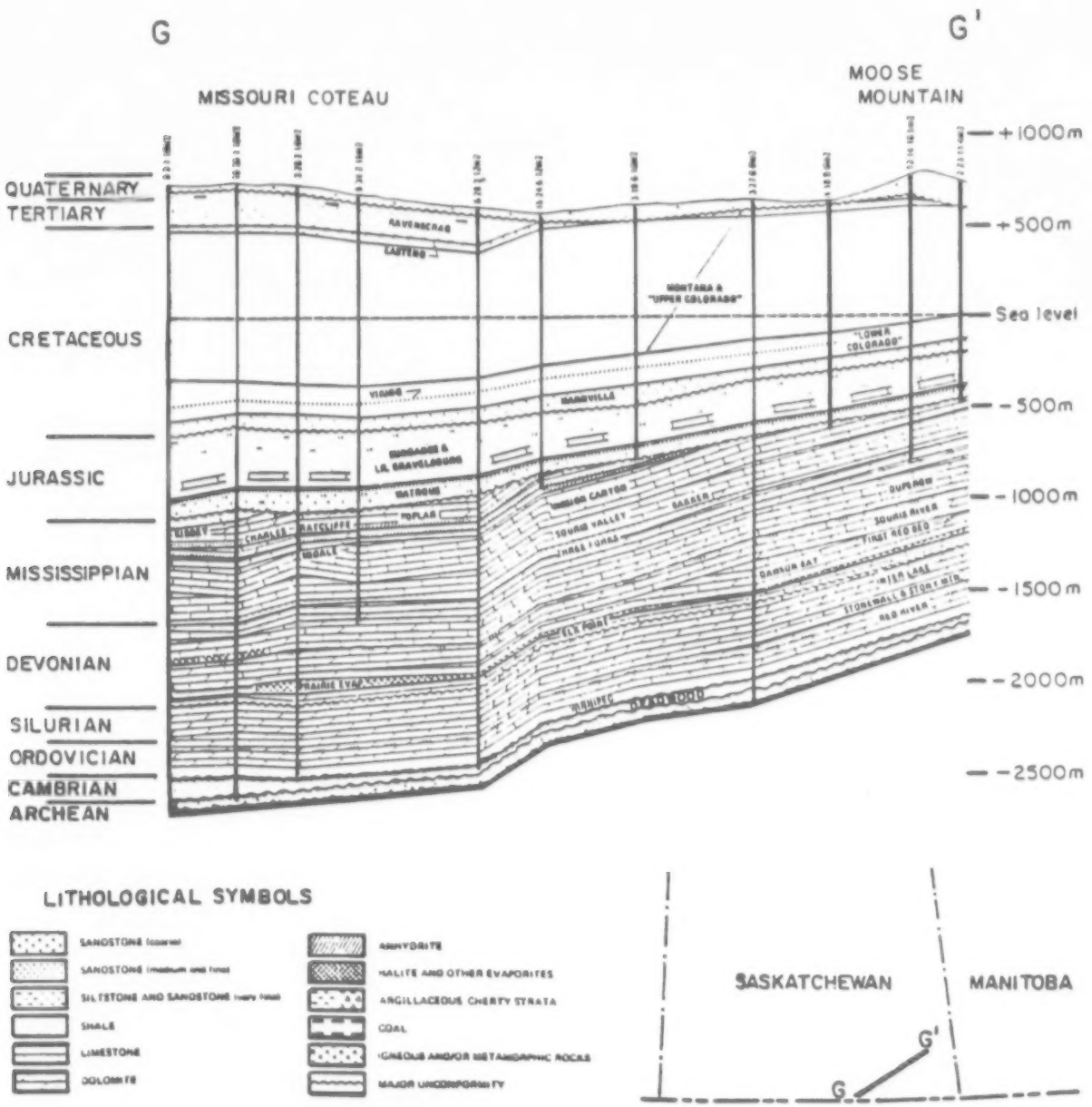


Fig. 11 Portion of northeasterly trending geological section G-G', illustrating stratigraphy and structure in this part of the Williston Basin (from Wright and Kent, 1984). Note the salt edge in the Prairie Evaporite and evidence of disturbance in overlying strata.

a river steepened by downstream tilt increases its sinuousity and deepens its channel. At a given discharge rate, uplift causes the river bottom to lower as the river scours in response to a steeper downvalley slope. Cross-sections of the Souris River channel at X-X' in reach AB and Y-Y' in reach BC indicate the channel is much wider and shallower along reach AB than along BC (Fig. 13). Where tilting occurs along fault block boundaries, the river channel would probably steepen toward the down-tilt side of the valley floor. If this tilt was toward the southwest it would be basinward. However, the present Souris River channel does not persistently follow the toe of the southwest valley wall along reach AB.

HYDROGEOLOGY AND HYDRODYNAMIC EFFECTS

If basement tectonism influenced the formation of Devonian reefs and anomalous surface features at Tableland, the locations and trends of buried valleys, elongate closed depressions, and perturbations in hydrodynamic and geothermic systems would likely have been influenced as well.

The regional trend of the buried Weyburn Valley northwest of Tableland is roughly N55°W, similar to that of the modern Souris River valley (Fig. 14). The southeasterly directed Weyburn Valley intersects the north-opening Estevan Valley a few kilometres northwest of Tableland. A northwesterly

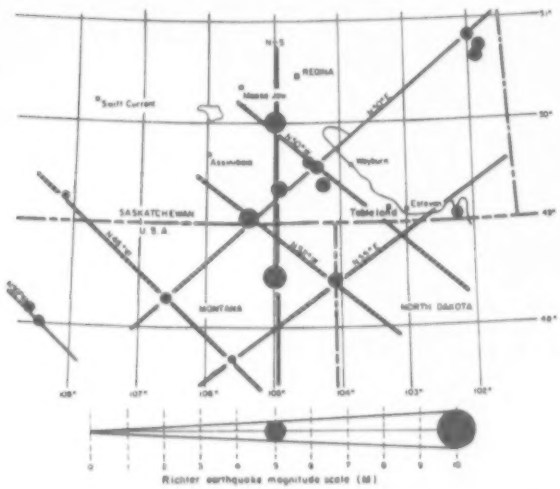


Fig. 12 Earthquake map showing northwesterly and northeasterly trends in the Williston Basin in southeastern Saskatchewan and neighbouring United States (from Earth Physics Branch, Canada Department of Energy, Mines and Resources, Victoria, British Columbia, 1977). Earthquake activity is thought to outline rigid fault-block boundaries.

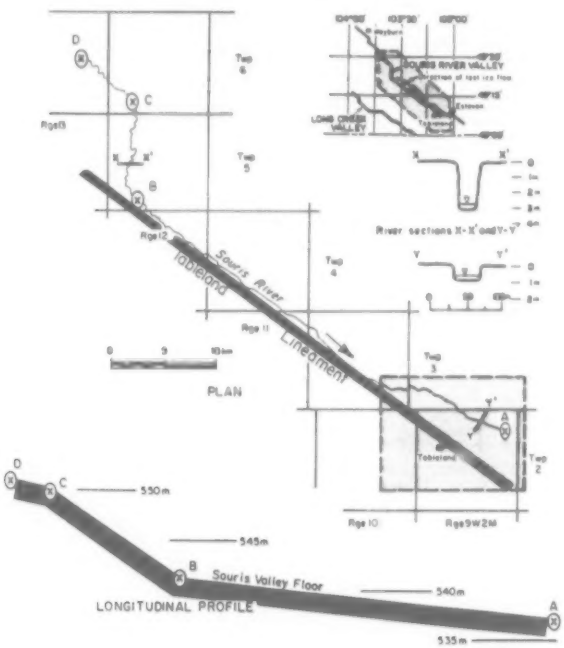


Fig. 13 A plan and profile illustrating changes in fluvial morphology, possibly related to active tectonics along the Souris River valley west of Tableland.

directed tributary is located south of Tableland and Home Oil's discovery well (Figs. 14 and 15). Just south of Tableland siding, over 55 m of glacial drift have been penetrated by boreholes whereas, at the nearby Home Oil oilwell location, the drift is only a metre or so thick on Tertiary sediments.

The orientation of the buried tributary south of Tableland roughly matches the trend of three pod-shaped coal deposits in the Paleocene Boundary coal horizon (Whitaker et al, 1978). These trends also align with the northwesterly suborthogonal reaches of the lower Long Creek valley inundated by the

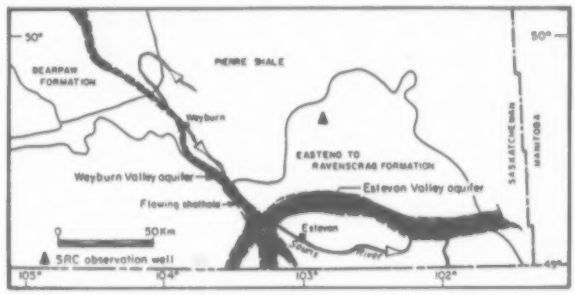


Fig. 14 Map of southeastern Saskatchewan showing the locations of two large buried (paleo-) aquifers: the Weyburn Valley aquifer and the Estevan Valley aquifer (from van der Kamp et al, 1986).

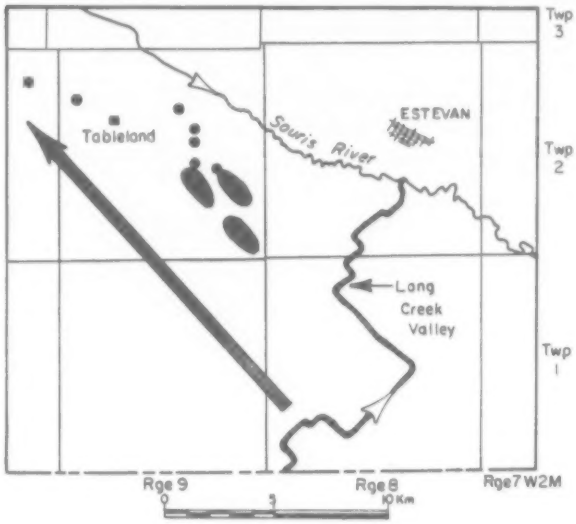


Fig. 15 The three lozenge-shaped areas (stippled) are anomalously thick podlike Tertiary Boundary coal seam deposits trending northwest-southeast in the Tableland area. Black dots are the sites of deep exploration holes and completed oilwells in the Devonian Winnipegosis Formation. The large arrow shows the approximate location of a major tributary buried valley filled with glacial drift. Note also the trends of suborthogonal reaches along lower Long Creek valley.

waters of the Boundary Dam reservoir (Fig. 15). The anomalously thick coal pods may, therefore, be related to deep hydrodynamics and associated Devonian salt dissolution acting along a northwest-trending lineament (Fig. 2). In an attempt to test this hypothesis further, a stratigraphic section across the Souris River valley and Tableland lineament was plotted from Plate 8 in Whitaker et al, 1978. The section penetrates the drift and Paleocene sediments and extends in to the Upper Cretaceous Frenchman and Bearpaw Formations (Fig. 16). Over 150 m of subsidence is indicated.

Artesian aquifers in the buried Weyburn and Estevan valleys discharge into the Souris River. Christopher (1980) indicates that, west of Estevan, the potentiometric surface in the Lower Cretaceous Mannville Group is well above ground surface south of the Souris River, but well below ground level north of it (Fig. 17), and that regional groundwater flow in this part of the Williston Basin is toward the northeast. Hitchon (1969) also shows waters in the Mannville and deeper Paleozoic aquifers to flow northeastwards (Fig. 18). A noteworthy feature of Christopher's map is the steepening of the potentiometric surface just south of the Souris River west of Estevan (Fig. 17). This suggests the presence of a local hydrodynamic

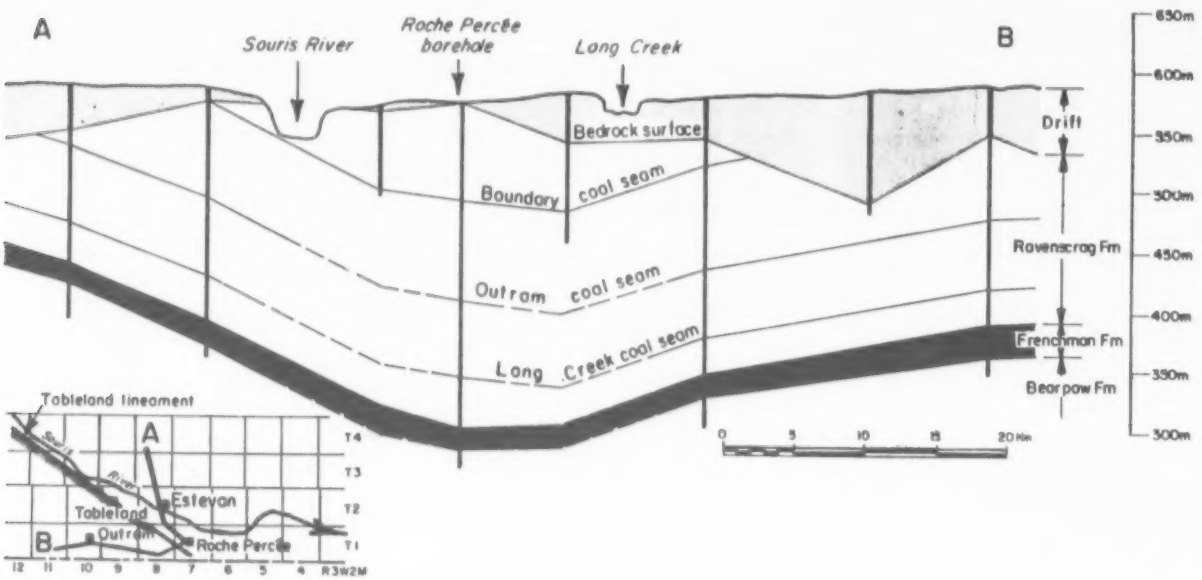


Fig. 16 A stratigraphic section in the Tableland area. Vertical lines are logged boreholes. The Ravenscrag Formation is Tertiary (Paleocene) in age, the Frenchman and Bearpaw Formations are Upper Cretaceous in age. Note the apparent subsidence of strata in the area south of the Souris River valley.

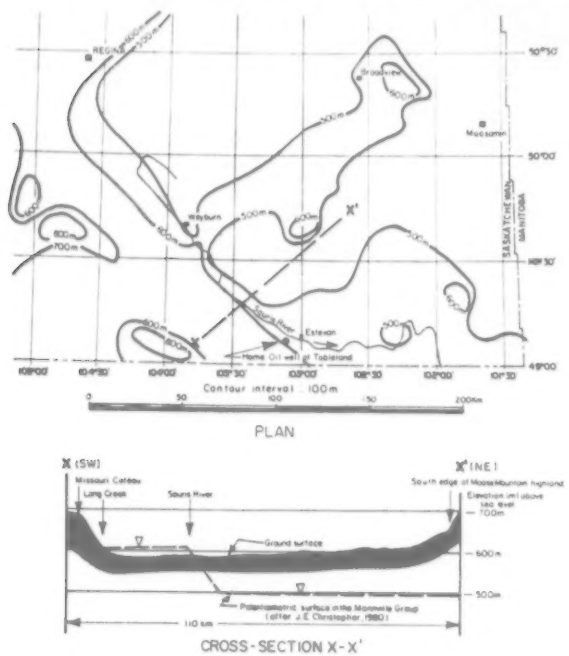


Fig. 17 Potentiometric surface in the Lower Cretaceous Mannville Group in southeastern Saskatchewan (from Christopher, 1980). Section X-X', located west of Tableland, shows an anomalously steep section roughly parallel to the Souris River valley west of the Home Oil well location at Tableland.

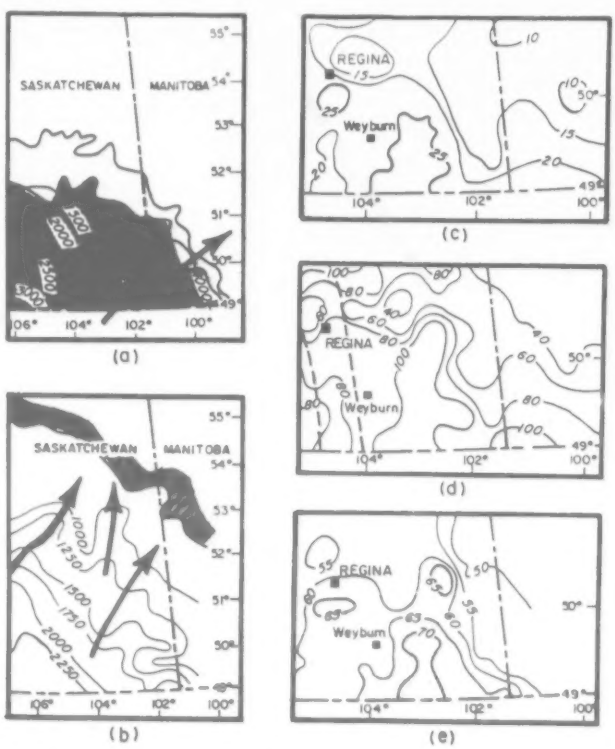


Fig. 18 (a) Potentiometric surface in the Lower Cretaceous Mannville Group. (b) Potentiometric surface in the Upper Devonian. Figures 18a and b are from Hitchon, 1969. (c) Geothermal gradient in °C/km in Paleozoic formations. (d) Heat flow in mW/m² in Paleozoic formations. (e) Temperature distribution in °C at 2 km depth below ground surface. Figures 18c, d and e are from Majorowicz et al, 1986.

restriction which may reflect substantial aquifer thinning or lower permeability caused by fault gouge or fault displacement. These effects may result from fault movement or differential salt dissolution and subsidence, or both.

Majorowicz et al (1986) show similar northerly and northeasterly geothermic patterns in the Williston Basin of southeastern Saskatchewan and southwestern Manitoba (Fig. 18c, d, e). They relate geothermic patterns in southeastern Saskatchewan to basin hydrodynamics and to hydrocarbon occurrences.

STRESS REGIMES

Several workers have suggested that surficial photolineament patterns are related in some way to regional joint patterns in bedrock (Overbey et al, 1974; Babcock, 1974; McCoy et al, 1986). Joint patterns in turn are frequently linked with paleo- and contemporary stress regimes (Overbey et al, 1974; Engelder and Geiser, 1980; Engelder, 1982; Bell and Babcock, 1986; Pauken et al, 1986; Stauffer and Gendzwill, 1987).

Although joints can be produced by mechanisms other than tectonic stress, fit patterns expected from assumed maximum principal horizontal compressive stress orientations. Possible paleo- and contemporary stress regimes should be sought, especially when 7 or 8 fracture sets appear in rose diagrams. Regional fracture sets may have been formed by collision of the African and North American plates sometime during the Paleozoic. Also trends that may have been sets of tension joints under one stress regime may become shear joints under another.

Two geometric elements can be identified in the patterns of photolineaments:
1) stronger and weaker sets that reflect variations in the length and frequency of photolineaments, and

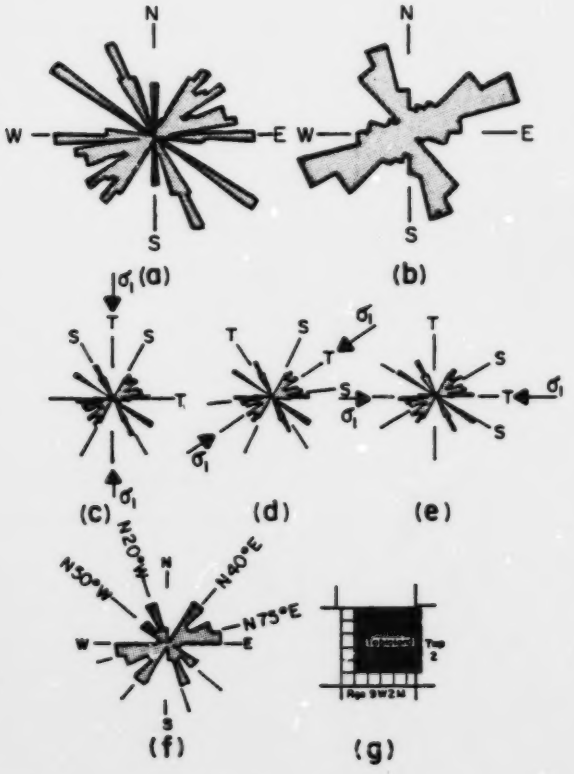


Fig. 19 (a) Rose diagram of 350 photolineaments in a 90 km2 ara in the Tableland area. From enhanced airphoto A21739-81. (b) Rose diagram of 150 till joints in LSD 6-15-2-9-W2M. The letters T and S indicate tensile and shear failure plane orientations that would have developed under the stress regimes, assuming a friction angle of 300 and the approximate maximum principal horizontal stress orientations, postulated by (c) Bell and Babcock, 1986, and also Brown, 1978; (d) Stauffer and Gendzwill, 1986; and (e) Thomas, 1974. (f) Rose diagram from same data as in (a) but based on a 15° instead of a 5° counting interval. Note that the suborthogonal N20°W and N40°E photolineament sets match the orientations of joint sets mapped in till, and that the N50°W and N40°E directions match the two preferred suborthogonal sets of bedrock fractures mapped by Stauffer and Gendzwill, 1986. (g) is a key map showing the area where photolineaments in (a) were mapped.

2) the intersection angle between different trends.
Both of these aspects are shown on rose diagrams, which may show up to 7 or 8 lineament sets to varying degrees (Fig. 3a).

The analyst of remotely sensed imagery tries to identify lineament sets sometimes referred to as genetically related "pairsets". The orientations of fracture planes are related to the direction of the major principal stress σ_1 Shear fractures are oriented at ($45^0 - \phi/2$ degrees to σ_1 where ϕ is the friction angle. Suborthogonal tensile fractures tend to be generally parallel and perpendicular to σ_1 (Fig. 19), whereas ductile failure deeper in the crust creates fractures oriented at 55^0 to σ_1 (Bijlaard, 1950; Mollard, 1957b). Therefore, dominant sets intersecting at about 90^0 suggest brittle fracture in a tensile stress field whereas, if ϕ is 30^0, intersection angles of about 60^0 suggest shear failure (Mollard, 1957b; Overbey et al, 1974; Brown, 1978; Pauken et al, 1986). On the other hand, intersection angles of about 110^0 between strongly developed lineament sets may reflect ductile deformation in the crust (Bijlaard, 1948, 1951; Mollard, 1957b).

Detailed mapping of 350 photolineaments in a 90 km² area around the Home Oil discovery shows four well developed sets, and three moderately developed sets that are only easily observed when the airphotos are enhanced (Fig. 3). Individual sets follow directions that commonly intersect at angles of about 60^0, 90^0, and 110^0. Mapped over large areas, mean directions of strong regional sets often show some local variation from these common interesection angles.

Figure 19 shows possible paleo- and contemporary stress orientations superimposed on rose diagrams of fracture sets identified in the Tableland area. Maximum principal horizontal compressive stress directions used in these constructions are those suggested by Bell and Babcock, 1986; Brown, 1978; Thomas, 1974; and Stauffer and Gendzwill, 1987. A friction angle of 30^0 has been assumed.

If the several sets of photolineament trends at Tableland match joint set directions, as a result of salt removal or differential compaction, and these fracture sets were pulled apart in tension like an expanding balloon, over time, they may open enough to allow entry of large amounts of surface water and groundwater. Higher permeability along the narrow zones of concentrated joint fractures would increase infiltration of water and cause differential surface and subsurface erosion to occur. In this way, the lineaments may reflect local differences in erosion, moisture content, plant growth, and soil tone. A related possibility is that differential salt dissolution and/or differential compaction may cause stretching over buried mounds and pinnacle reefs, forming multisided polygons that, when eroded into slight depressions at ground surface, develop subcircular ring and arclike features in the microrelief, drainage, and soil tones (Fig. 7).

PROPOSED GENETIC MODEL

Hodgson (1965, 1976, 1977, 1985) has discussed in considerable detail the origin and characterisitics of fracture systems, the genetic and geometric relations between structures in the basement and the overlying sedimentary rocks, and the role of fracture systems in near-surface geochemical prospecting for oil and gas. Much of the data and many of the ideas presented by Hodgson have guided formulation of the genetic model proposed for the Tableland deep oil area.

Based on data presented in this paper the following genetic model is postulated: The Williston Basin is underlain by large

rigid basement blocks seperated by ductile zones. The blocks are identified from fault, lineament, and earthquake patterns, with larger blocks often surrounded by earthquake activity. Sedimentary rock units over basement faults at block boundaries appear to be affected by periodic fault movements as indicated by facies changes, thickness changes, high-angle faults and warps (Kent, 1973, 1974, 1987; Thomas, 1974; Gallagher, 1981). Deformation in the ductile basement thus affects overlying sedimentary rocks. Fault blocks respond to contemporary boundary forces associated with plate-tectonic motion. It is also significant that all rocks are weaker in tension than in compression.

Significant basement features (ridges, faults, hinge lines, etc.) may also have controlled selective northwest-trending ancient strandlines, shoaling and reefing, and facies and thickness changes in the Devonian Winnipegosis Formation west of Estevan (Fig. 20). Likewise periodic movements along these zones may have been responsible for continuing salt dissolution, related ongoing differential subsidence, and surface patterns that show up on remotely sensed imagery. Removal of salt in the Prairie Evaporite has likely been active throughout much of post-Middle Devonian time, and may have accentuated the photolineament- and ring-patterns in the Tableland area. Although tectonic stresses operating within smaller lineament blocks may not always match regional trends, fundamental Precambrian fault block patterns probably persisted through Phanerozoic time, resulting in the perpetuation of deep crustal fracture systems in overlying sedimentary rock units. Such fracture systems appear to have influenced hydrodynamic and geothermic effects and patterns, and even associated hydrocarbon occurrences in Paleozoic and Mesozoic sediments in southeastern Saskatchewan (Hitchon, 1969; Majorowicz et al, 1986).

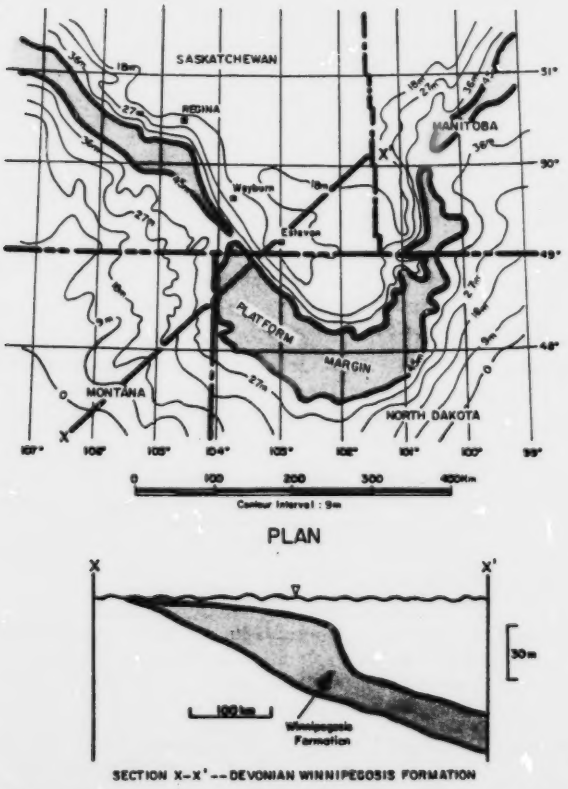


Fig. 20 Isopach map of the Devonian Winnipegosis Formation showing strandline trend in southeastern Saskatchewan and neighbouring United States (from Kissling and Ehrets, 1986).

IMPLICATIONS FOR DEEP OIL SEARCH STRATEGIES

In developing search strategies for deep hydrocarbon exploration, the analysis of remotely sensed lineament data is likely to lack proper focus in the absence of correlatable subsurface data. Surface lineament and ring features should be closely correlated with subsurface geological data to achieve useful results. This includes synthesis, correlation and integration of relevant geological, geophysical, geochemical, hydrogeological, biogeochemical, and geothermal data. Desirably, remotely sensed lineament pattern data should be compared and correlated first with basement magnetic and gravity lineament data. Where basement- and surface-trends appear to match, petroleum traps between them may have been influenced as well. Correlation of surficial and basement lineaments may be followed by a search for breaks in seismic reflection data and indications of significant hydrogeological features (paleovalleys, changes in potentiometric surfaces, hydrochemistry). Near-surface soil gas, soil geochemical (salinity, carbonate, hydrocarbon), and biogeochemical or geobotanical data may also be correlated when they are available. Bacteria-driven (microbial) soil and vegetation reactions may be caused by light hydrocarbon (ethane, propane, butane) microseepages ascending along fracture pathways.

In the remote sensing of large areas, the most important indicators are:

a) well expressed, unusually high-density lineament zones;
b) several pronounced lineament sets, and additional minor directions;
c) single lineaments that are long and conspicuous, and accentuated locally by erosion;
d) abrupt change in dominant lineament orientation and density;
e) accentuation of preferred directions in the surface drainage pattern;
and f) ringlike features in the landscape.
All these features have been observed in the Tableland deep oil area.

ACKNOWLEDGEMENTS

Much of the recent data contained in this paper were developed during the course of a provincial/federal government research study contract titled "Remote Sensing for Petroleum Exploration and Exploitation in Saskatchewan." That study is still in progress, and involves three study areas in Saskatchewan. The work is scheduled for completion in August, 1987. I thank Dr. J. E. Christopher and Dr. M. A. Wilson, Saskatchewan Energy and Mines, and Mr. Stan Kanik, EMR, Ottawa, for permission to present data developed for the Tableland area. Thanks also go to Lynden Penner for mapping photolineaments and fractures in till, and for many helpful discussions. I also thank N. Karpuik for drafting the figures and Mrs. C. Radiff for typing the manuscript.

REFERENCES CITED

Babcock, E. A., 1974. Photolineaments and regional joints: lineament density and terrain parameters, south-central Alberta. Bull. Can. Petrol. Geol., v. 22, no. 2, p. 89-105.

Bell, J. S., and E. A. Babcock, 1986. The stress regime of the Western Canadian Basin and implications for hydrocarbon production. Bull. Can. Petrol. Geol., v. 34, no. 3, p. 364-378.

Bendefy, L., J. Dohnalik, and K. Mike, 1967. Nouvelles methodes de l'etude genetique des cours d'eau. Int. Assoc. Sci. Hydrology, Publ. 75 (Bevue), p. 64-72.

Bijlaard, P. P., 1948. On the linear patterns of the Earth's crust. Proc. Kon Akada, Wetensch., Amsterdam, v. 51, no. 4, p. 450-456.

Bijlaard, P. P., 1951. On the origin of geosynclines, mountain formation, and volcanism. Trans. Am. Geophysical Union, v. 32, no. 4, p. 518-519, 526, 535.

Brown, D. L., 1978. Wrench fault deformational patterns associated with a meridonal stress axis recognized in Paleozoic rocks in parts of Montana, South Dakota, and Wyoming. In: Rehig D., Chairman, The Economic Geology of the Williston Basin. Montana Geol. Soc. 24th Ann. Conf. 1978, Williston Basin Symposium.

Christiansen, E. A., 1956. Glacial geology of the Moose Mountain area, Saskatchewan. Saskatchewan Department of Mineral Resources, Report No. 21, 35 p.

Christopher, J. E., 1980. The Lower Cretaceous Mannville Group of Saskatchewan — a tectonic overview. In: L. S., Beck, J. E., Christopher, and D. M. Kent, eds., Lloydminster and Beyond. Sask. Geol. Soc. Spec. Publ. No. 5, p. 3-32.

Engelder, T., 1982. Is there a relationship between selected regional joints and contemporary stress within the lithosphere of North America? Reply to A. Scheidegger. Tectonics, v. 1, no. 5, p. 465-470.

Engelder, T., and P. Geiser., 1980. On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York. J. Geophys. Res., v. 85, p. 6319-6341.

Erickson, K., 1970. Surficial lineaments and their structural implications in the Williston Basin. M. Sc. thesis, University of North Dakota, Grand Forks.

Gallagher, J. J. Jr., 1981. Tectonics of China: continental scale cataclastic flow. In: Carter, N. L., M. Friedman, J. M. Logan, and D. W. Stearns, eds., Mechanical behaviour of crustal rocks. Geophysical Monograph 24, p. 259-273.

Gerhard, L. C., 1986. Lineament applications to development of exploration strategy in the Williston Basin. Proceedings, Second Workshop on Remote Sensing/ Lineament Applications for Energy Extraction, U.S. Department of Energy, Office of Fossil Energy, Morgantown Energy Technology Center, Morgantown, West Virginia, p. 66-80.

Hitchon, B., 1969. Fluid flow in the Western Canada sedimentary basin, 2: effect of geology. Water Resources Res., v. 5, p. 460-469.

Hodgson, R. A., 1965. Genetic and geometric relations between structures in basement and overlying sedimentary rocks, with examples from Colorado Plateau and Wyoming. Bull. Am. Assoc. Petrol. Geol., v. 49, no. 7, p. 935-949.

Hodgson, R. A., 1987. Fracture systems: characteristics and origin. Proc. of the Seventh Annual Appalachian Petroleum Geology Symposium, p. 54-74.

Hodgson, R. A., 1977. Hierarchy of fracture systems and their origins. International Symposium on Tectonics and Volcanism of Planets, Institute of Geological Sciences, Erevan, Aremenia, USSR.

Hodgson, R. A., 1985. The role of natural fracture systems in near surface geochemical prospecting. Paper presented at Amer. Chem. Soc. 190th National Mtg., Chicago, Ill.

Holter, M. E., 1969. The Middle Devonian Prairie Evaporite of Saskatchewan. Saskatchewan Department of Mineral Resources, Report No. 123, 134 p.

Kehew, A. E. 1982. Catastrophic flood hypothesis for the origin of the Souris Spillway, Saskatchewan and North Dakota. Geol. Soc. Am. Bull., v. 93, p. 1051-1058.

Kehew, A. E., and M. L. Lord, 1986. Origin of large-scale erosional features of glacial-lake spillways in the Northern Great Plains. Geol. Soc. Am. Bull., v. 97, p. 162-177.

Kent, D. M., 1973. Paleozoic hydrocarbon reservoirs in Saskatchewan and their relationship to basement lineaments. Journal of Canadian Petroleum Technology, July-September.

Kent, D. M., 1974. The relationship between hydrocarbon accumulations and basement structural elements in the northern Williston Basin. In: Parslow, G.R. ed., Fuels: a Geological Appraisal. Sask. Geol. Soc. Spec. Publ. No. 2, p. 63-79.

Kent, D. M., 1987. Paleotectonic controls on sedimentation in the northern Williston Basin, Saskatchewan. In: J. A. Peterson, D. M. Kent, S. B. Anderson, R. H. Pilatzke and M. W. Longman, eds., Williston Basin: Anatomy of a Cratonic Oil Province, Rocky Mountain Association of Geologists.

Kissling, D. L., and J. R. Ehrets, 1986. Devonian reservoirs, southeastern Saskatchewan: an exploration evaluation. Unpublished report, Jackalope Geological Ltd., Boulder, Colo.

Marjorowicz, J. A., F. W. Jones, and A. M. Jessop, 1986. Geothermics of the Williston Basin in Canada in relation to hydrodynamics and hydrocarbon occurrences. Geophysics, v. 51, no. 3, p. 767-779.

McCoy, R. M., M. J. Havertz, K. Clem, C. Brandt and S. Young, 1986. Associations among lineaments, subsurface fractures, hydrocarbon microseepage, and production in the Uinta Basin, Utah. Fifth Thematic Conference on Remote Sensing for Exploration Geology, Reno, Nevada; Preprint, 14 p.

Merin, I. S., and W. R. Moore, 1986. Application of Landsat imagery to oil exploration in Niobrara Formation, Denver Basin, Wyoming. Am. Assoc. Petrol. Geol. Bull., v. 70, no. 4, p. 351-359.

Michael, D. C., and I. S. Merin. 1986. Tectonic framework of Powder River Basin, Wyoming and Montana, interpreted from Landsat imagery: Discussion. Am. Assoc. Petrol. Geol. Bull., v. 70, no. 4, p. 453-455.

Mollard, J. D., 1957a. Aerial photographs aid petroleum search in Saskatchewan. Canadian Oil and Gas Industries Journal, July, 8 p.

Mollard, J. D., 1957b. Aerial mosaics reveal fracture patterns on surface deposits in southern Saskatchewan and Manitoba. Oil in Canada, August, 11 p.

Mollard, J. D., 1958. Aerial fracture pattern study as a tool in subsurface investigations v. I — A working manual (142 p.); v. II — A compilation of research work, (320 p.). Unpublished report, J. D. Mollard and Associates Limited, Regina, for Imperial Oil Limited, Calgary, Alberta, and California Standard Research, La Habra, California.

Mollard, J. D., 1959. Photogeophysics: its application in petroleum exploration over the glaciated plains of western Canada. Proceedings Second Williston Basin Conference, North Dakota Geol. Society, p. 109-117.

Mollard, J. D., 1984. Extraordinary landscape patterns: a quest for their origins. Can. Journ. of Remote Sensing, v. 10, no. 2, p. 121-134.

Overbey, W. K. Jr., W. K. Sawyer, and B. R. Henriger, 1974. Relationships of earth fracture systems to productivity of a gas storage reservoir.: U. S. Bureau of Mines Report of Investigations 7952, United States Department of the Interior, 133 p.

Pauken, R. J., J. H. Griffith, and J. H. Halsey, 1986. Fracture patterns and production trends, Big Sandy Field, Eastern Kentucky. Fifth Thematic Conference on Remote Sensing for Exploration Geology, Reno, Nevada; Preprint, 24 p.

Penner, L. A., and M. J. Reeves, 1986. Fracture patterns, strength and hydraulic conductivity in Saskatchewan tills. Proceedings, Third Can. Hydrogeological Conference, International Association of Hydrogeologists, Saskatoon, p. 83-91.

Sanford, B. V., F. J. Thompson and G. H. McFall, 1985. Plate tectonics — a possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario: Bull. Can. Petrol. Geol., v. 33, no. 1, March, p. 52-71.

Schumm, S. A., 1986. Alluvial river response to active tectonics. In: Active Tectonics, National Academy Press, Washington, D. C., p. 80-94.

Shurr, G. W., 1978. Paleotectonism, gas potential in West: The Oil and Gas Journal, Nov. 6, p. 98-103.

Siegal, B.S., and A. R. Gillespie, 1980. Remote sensing in geology. John Wiley and Sons, 702 p.

Slack, P., 1981. Paleotectonics and hydrocarbon accumulation, Powder River Basin, Wyoming. Bull. Am. Assoc. Petrol. Geol., v. 65, p. 730-743.

Stauffer, M. R., and D. J. Gendzwill, 1987. Fractures in the central prairies, stream patterns, and the mid-continent stress field . Can. Jour. Earth Sciences.

Thomas, G. E., 1974. Lineament block tectonics: Williston-Blood Creek Basin. Bull. Am. Assoc. Petrol. Geol. Bull., v. 58, no. 7, p. 1305-1322.

Van der Kamp, G., H. Maathuis, and W. A. Meneley, 1986. Bulk permeability of a thick till overlying the buried valley aquifer near Weyburn, Saskatchewan. Proceedings, Third Canadian Hydrogeological Conference, International Association of Hydrogeologists, Saskatoon, Saskatchewan, p. 93-100.

Whitaker, S. H., P. L. Broughton, and J. A. Irvine, 1978. Coal resources of southern Saskatchewan: A model for evaluation methodology. Saskatchewan Research Council Report 20, Saskatchewan Mineral Resources Report 209 and Geological Survey of Canada Ec. Geol. Report 30.

Wilson, W., D. L. Surjik, and H. G. Sawatsky, 1963. Hydrocarbon potential of the south Regina area, Saskatchewan. Saskatchewan Department of Mineral Resources, Report No. 76, 17 p.

Worsley, N., and A. Fuzesy, 1979. The potash bearing members of the Devonian Prairie Evaporite of southeastern Saskatchewan, south of the mining area. Economic Geology, v. 14, p. 377-388.

Wright, G. N., and D. M. Kent, 1984. A series of geological sections illustrating the Western Canada sedimentary basin. The Canadian Society of Petroleum Geologists and The Geological Association of Canada.

Zuchiewicz, W., 1979. A possibility of application of the theoretical longitudinal river's profile analysis to investigations of young tectonic movements. Ann. Soc. Geol. Pologne 49., p. 327-342.

LATE CENOZOIC EROSION OF WILLISTON BASIN SEDIMENTS

ERIC N. CLAUSEN
Division of Science
Minot State University
Minot, North Dakota 58701

ABSTRACT

Evidence for deep erosion of sediments in the Williston Basin region can be found throughout western North Dakota, eastern Montana, southern Saskatchewan, southwestern Manitoba, southeastern Alberta, and northwestern South Dakota. Evidence includes an erosion surface cutting across numerous stratigraphic units, a system of major escarpments, erosional remnants of previous topographic surfaces, and high-level drainage divides covered with alluvial sediments. Glacial erosion, aided by tremendous volumes of meltwater, probably scoured out systems of extremely wide and shallow glacial troughs on the northern Great Plains. These valleys are cut in the easily-eroded claystone bedrock of the region. The Missouri Escarpment, the Manitoba Escarpment, and escarpments bounding upland regions such as the Prairie Coteau, the Turtle Mountains, Moose Mountain, Riding Mountain, Duck Mountain, Porcupine Mountain and the Pasquia Hills are remnants of the walls of some of these valleys.

Late Cenozoic climatic models indicate as many as 25 major glacial episodes during the past 3.2 million years. Continental icesheets probably advanced into the Williston Basin region during most, if not all, of those glacial episodes. Alpine icecaps probably covered the Rocky Mountain uplands during each of the glacial episodes. Meltwater from these alpine icecaps repeatedly crossed the Williston Basin region only to be diverted along the margins of continental ice sheets. Glacial meltwater rivers, emanating from alpine icecaps in the Rocky Mountain region, carried distinctive glacio-fluvial alluvium. Gravels, capping upland regions in eastern Montana and the western Dakotas and elsewhere were probably deposited when rivers, carrying such glacio-fluvial material, were diverted along continental ice margins. Evidence for early diversions of one such river, the Yellowstone River, can be found along the asymmetric drainage divide east of the Little Missouri River. Buttes, composed of sediments usually mapped as (Oligocene) White River Group, probably represent topographic inversions of early Yellowstone River valleys. The distinctive sediments record both the diversions of the rivers and the progressive lowering of the Williston Basin region landscape.

INTRODUCTION

Deep erosion of the northern Great Plains is evident from the present-day erosion surface which cuts across units representing a wide range of geologic ages in the Williston Basin region. The Bedrock Geologic Map of North Dakota (Carlson, 1969) shows significant exposures of rocks ranging in age from Precambrian in the east to Eocene and younger in the west. Thornbury (1965) describes a perplexing difference between the northern Great Plains and the High Plains section to the south of it. Tertiary sedimentation appears to have continued in the southern High Plains through the Pliocene with the deposition of the Ogallala sediments. Tertiary sedimentation in the northern Great Plains is today represented by a fairly complete Paleocene section, limited exposures of Eocene rock, isolated patches of White River Group sediments and not much else. The northern Great Plains erosion surface is generally recognized, however, no concensus has been reached on how or when the erosion surface formed. The purpose of this paper is to present a model which may explain the present-day erosion surface and the sharp differences between the northern Great Plains and the southern High Plains. This model assumes substantial erosion of the northern Great Plains has taken place during the past three million years which coincides with the period of major glacial episodes on the North American continent.

MAJOR ESCARPMENTS OF THE NORTHERN GREAT PLAINS

The Missouri Escarpment in North Dakota, Saskatchewan, and South Dakota is one of several major escarpments in the northern Great Plains region of North America. Other escarpments with somewhat similar characteristics bound upland areas such as the Prairie Coteau, the Pembina Mountains, the Turtle Mountains, Riding Mountain, Moose Mountain, Duck Mountain, the Porcupine Hills, and the Pasquia Hills (figure 1). These escarpments represent rises of 100 to 300 metres above the surrounding plains. Between some of these escarpments are relatively flat lowlands of varying width — with some exceeding 200 kilometers in width. These escarpments are remarkably smooth and straight.

Fig. 1 Sketch map illustrating the position of some of the major northern Great Plains escarpments discussed in this paper.

A variety of hypotheses have been presented in the literature to explain the origin of these escarpments. Lemke (1960) proposed a synclinal valley between the Missouri Plateau and the

Turtle Mountains. Erickson (1970) suggested the Missouri Escarpment may be the expression of a major transcurrent fault. He proposed uplands such as the Turtle Mountains and Moose Mountain may be bounded by wrench faults. Bluemle (1978) proposed spring sapping followed by glacial erosion for the origin of the Pembina Escarpment. Hypotheses, such as these, assume the escarpments predate glaciation. The escarpments are cut in easily-eroded claystone bedrock and probably would not have survived the erosive effects of ice and large volumes of meltwater during multiple glacial periods.

Flint (1955) proposed lateral erosion by glacier ice to explain the smooth character of the Missouri Escarpment and the escarpments bounding the Prairie Coteau in South Dakota. Flint argued the James River Lowland between the Missouri Escarpment and the Prairie Coteau was cut during glacial time by a combination of river downcutting and lateral erosion by glacial ice. While Flint proposed glacial erosion as an important factor in producing the James River Lowland he did not recognize deep glacial erosion on the Great Plains in general.

The idea of deep glacial erosion of the northern Great Plains and other regions was introduced by White in 1972. White suggested that erosion by Pleistocene continental ice sheets removed stratigraphic cover to exhume the Precambrian Shield in North America. White went on to suggest that erosion by continental ice sheets has carved great hierarchies of ellipsoidal basins. Escarpments in the northern Great Plains region, such as the Missouri Escarpment and the Manitoba Escarpment can be related to White's hierarchies of ellipsoidal basins.

White's hypothesis was not well received. Strong opposition came from Sugden (1976), Gravenor (1975), and Chumakov (1973) among others. Major evidence cited in opposition to White's hypothesis related to the depth of erosion of the Precambrian Shield, the thinness of glacial drifts found on the continent, the apparent lack of sufficient quantities of Pleistocene sediments in marine basins adjacent to the North American continent and the failure of glacial geologists to locate evidence of early glacial moraines lacking debris from the Precambrian Shield. White's hypothesis has generally been ignored by geologists working in the northern Great Plains region.

Oceanographic evidence does, though, lend support for White's hypothesis. Climatic models based on oxygen isotope studies of oceanic sediments have been used to confirm variations in the earth's orbit as a possible cause of glacial episodes and to infer periods of glaciation at intervals of approximately 100,000 years (Imbrie and Imbrie, 1979, based on data from Hays, Imbrie, and Shackleton, 1976, and others). Generally accepted climatic models based on oceanographic data suggest the possibility of as many as 25 major glacial episodes during the past three million years (Bell and Laine, 1985). The cummulative erosion of 25 major glacial episodes might be of a very different order of magnitude than the erosion which occurs during a single glacial episode. Further, Bell and Laine (1985) report sufficient sediments adjacent to the North American continent to suggest an average of at least 120 meters of material has been removed from the glaciated regions of the continent in the last three million years. The claystone bedrock of the northern Great Plains region is more easily eroded than bedrock materials found elsewhere on the continent. Bell and Laine's data may indicate substantially more than 120 meters of erosion in the northern Great Plains region. The idea of deep glacial erosion as a direct or indirect cause of the northern Great Plains escarpments appears to be supported.

A MODEL FOR DEEP GLACIAL EROSION

The Missouri Escarpment; the Pembina Escarpment; the escarpments flanking the Turtle Mountains, the Prairie Coteau, and various upland regions of Manitoba and in Saskatchewan appear to be the walls of large glacial through valleys. Each of these glacial through valleys probably originated as an ice-marginal diversion channel or as a glacial meltwater valley flowing into an ice-marginal diversion channel. The ice-marginal diversion channels were oriented in a northwest-southeast direction while meltwater streams came into these channels from the northeast. Advancing ice flowed south through the southwest-trending meltwater channels and then proceeded to flow into the southeast-trending ice-marginal diversion channels. This process was probably repeated numerous times as ice advanced over the region.

Lateral erosion by the ice and tremendous volumes of meltwater widened what had started out as relatively narrow river valleys. Valley walls composed of easily-eroded Cretaceous and Tertiary claystones offered no resistance as a system of extremely wide and shallow "U" shaped glacial troughs was produced on the Great Plains. The Missouri Escarpment represents the west wall of one such through valley which originated as an ice-marginal river valley. The southwest flanks of Moose Mountain and the Turtle Mountains and the west flank of the Prairie Coteau represent all that is left of the east wall of this through valley. The Manitoba Escarpment, the Pembina Escarpment, and the east flank of the Prairie Coteau represent all that is left of the west wall of another glacial through valley. The east wall of that valley has been completely eroded away. The northeast-southwest trending lowland between Moose Mountain and the Turtle Mountains represents just one of several glacial through valleys which originated as meltwater valleys in front of an advancing ice sheet.

At times the ice filling these valleys thickened sufficiently to spill over onto adjacent upland areas. The Missouri Coteau and thick morainal deposits adjacent to other escarpments in effect represent remnants of large-scale lateral moraines bounding the walls of these glacially-carved through valleys. The escarpments may provide a measure of the thickness of the continental ice sheets which covered the northern Great Plains region.

The heights of the escarpments also provide a minimum estimate of the glacial erosion which has occurred in the region. For example, 100 to 300 meters of easily-eroded Cretaceous and Tertiary claystone were probably removed by glacial erosion from the region between the Missouri Escarpment and the Turtle Mountains. How many glacial episodes were required to produce this amount of erosion is not known. While multiple glacial tills can be found in the lowlands between the escarpments, there is no evidence to suggest any of these tills date back to the earliest glacial episodes. Perhaps, glacial erosion of this type stripped off several hundred meters of similar sediments before the cycle which resulted in the modern escarpments began. Other types of evidence are needed to determine the full magnitude of erosion which has taken place since the first continental icesheet in the region.

EVIDENCE BASED ON FREE-STANDING GLACIAL ERRATICS

West and south of the Missouri River trench in South and North Dakota free-standing glacial erratics, with little or no inclosing matrix or fine-grained drift of any kind, are used to mark the position of maximum ice advance. These boulders appear to represent the residual concentrate of the coarsest element of extensive glacially-deposited sediments which had covered a topographic surface now largely removed. Glacial landforms are totally absent. At least 60 meters of erosion has occurred in many areas since the earliest advance (Clayton, 1969). A case can be made for even more erosion. A wind gap between North and South Killdeer Mountains in Dunn County, North Dakota was apparently occupied by a meltwater stream which was then diverted by glacial ice. If that same stream cut the gap, which seems reasonable to assume, then over 250 meters of erosion can be documented in the Killdeer Mountain region.

Clayton, Moran and Bluemle (1980) suggest there are fewer lag boulders present in areas glaciated during the earliest glacial advances than in areas glaciated at later times. Differences between lag boulder concentrations may be partially explained with a hypothesis that lag boulders accummulate with successive glacial advances. The differences in lag boulder concentrations may also be explained by the increasing glacial erosion of hard rock types from the Canadian Shield with time. This second hypothesis is consistent with White's (1972) prediction that the Canadian Shield was covered with sediments prior to the start of the late Cenozoic glacial period. If the Canadian Shield was covered with claystones and other easily-eroded sediments then the earliest glacial events may not have included any erratics of typical Canadian Shield rock types.

If the Canadian Shield was covered with claystone sediments at the start of the Late Cenozoic glacial period and Canadian Shield rock types were not included in the early glacial moraines then what types of evidence will permit us to recognize the earliest glaciations? The early moraines probably did not differ significantly in resistance to erosion from the underlying claystone bedrock of the northern Great Plains. Erosion has probably removed most, if not all, of the claystone moraines which would have been left by these early glaciers and also some of the underlying claystone bedrock. Evidence for these early glacial advances probably can not be recognized using traditional techniques and lines of evidence.

The earliest glaciations, if they existed, may be recognized by studying rivers which were diverted along the edges of the early ice sheets. Rivers, such as the Yellowstone and the Missouri, head in the Rocky Mountains in areas which were probably glaciated whenever continental ice sheets existed on the northern Great Plains (see Montagne, J., 1972). These rivers flow northeast and would have been blocked and diverted to the southeast by continental ice sheets whenever the continental ice sheets existed. These rivers probably included tremendous volumes of meltwater and carried large quantities of distinctive glacio-fluvial material whenever there were large alpine glaciers in the mountains. This glacio-fluvial material should serve as excellent marker material which can be used to trace the diversions of the rivers along the continental ice margins.

EVIDENCE BASED ON YELLOWSTONE RIVER HISTORY

The modern Missouri River has long been recognized to have formed as an ice-marginal river (Todd, 1914). An abandoned valley extending north from Williston, North Dakota has also long been recognized as an abandoned valley of the Yellowstone River which once flowed north. The Geologic Map of North Dakota (Clayton, 1980) shows ice margins south of any recognized ice-marginal river channels. The northeast-flowing Yellowstone River must have been diverted by these ice margins and evidence for these diversions should exist.

Evidence for numerous abandoned Yellowstone River channels crossing southwest North Dakota and northwest South Dakota can be found along the asymmetric drainage divide between the Little Missouri River and the southeast-flowing Knife, Heart, Cannonball, Grand and Moreau Rivers. This evidence suggests the northeast-flowing Yellowstone River was repeatedly diverted in eastern Montana to flow southeast across North Dakota. These diversions appear to have taken place near recognized glacial margins.

Numerous rounded pebbles and cobbles of a distinctive quartz latite porphyry, characteristic of Yellowstone River alluvium, can be found in the Knife, Heart, Cannonball, Grand and Moreau River valleys. The distinctive porphyry is present in lag gravels crossing the asymmetric divide between the Little Missouri River and the Knife, Heart, Cannonball, Grand and Moreau Rivers. The distinctive porphyry is also common in conglomeratic units which have been mapped as Oligocene White River Group at Chalky Buttes-White Butte in Slope County, at East and West Rainy Buttes in Slope County, and at the Little Badlands in Stark County (Clayton, 1980). These (White River Group) deposits probably represent early Yellowstone River channels. Topographic inversion since the deposition of the sediments has produced the buttes we see today.

A northwest-southeast alignment of many secondary streams and rivers can be observed on topographic maps of eastern Montana, northwest South Dakota and southwest North Dakota. Barbed tributaries enter the northeast-trending Yellowstone River Valley from both the northwest and the southeast. Barbed tributaries enter the north-trending Little Missouri Valley from the northwest. The north-flowing Little Missouri River turns in McKenzie and Dunn counties to flow southeast for a significant distance. A major asymmetric drainage divide separates the north-trending Little Missouri River from the southeast-flowing Knife, Heart, Cannonball, Grand and Moreau Rivers. Most tributaries of the Knife, Heart, Cannonball, Grand and Moreau Rivers also show a strong northwest-southeast orientation. The Little Missouri River appears to have captured the upper reaches of the Knife, Heart, Cannonball, Grand and Moreau Rivers which prior to capture probably extended to an area west of the present-day Yellowstone River Valley.

A northwest-southeast alignment of buttes can be seen in southeastern Montana, northwestern South Dakota and southwestern North Dakota. The Long Pine Hills in Carter County, Montana and the West and East Short Pine Hills in Harding County, South Dakota show the same northwest-southeast orientation that can be seen in the regional drainage network. The north end of Slim Buttes in Harding County, South Dakota is oriented in a north-south direction while the south end is oriented in a northwest-southeast direction. The Chalky Buttes-White Butte complex in Slope County, North Dakota is oriented in a north-south direction with a spur at the

southern end to the southeast. West and East Rainy Buttes show the same northwest-southeast orientation. These buttes probably represent sediments which had filled narrow valleys of early southeast-trending Yellowstone River channels which crossed the region. Erosion, inverting the topography, has produced the modern buttes composed of early Yellowstone River alluvium.

Rounded boulders and cobbles of quartzite and granite can be found associated with conglomeratic units found at the base of sediments usually mapped as (Oligocene) White River Group at the Short Pine Hills, at Slim Buttes, at Chalky Buttes-White Butte, at the Rainy Buttes and at the Little Badlands. The largest boulders exceed 60 centimeters in diameter. These rounded boulders and cobbles indicate the presence of a major river at each locality.

Gill (1962) and Toepelman (1925) mapped landslide blocks developed along the southwest and northeast walls of what may have been a series of valleys trending in a northwest-southeast direction. These landslide blocks are present in the Short Pine Hills and Slim Buttes regions of Harding County, South Dakota. The landslide blocks include sediments usually mapped as (Oligocene) White River Group and are overlain by sediments usually mapped as (Miocene) Arikaree. Landslide blocks along one northwest-southeast oriented former valley in the Short Pine Hills suggest the valley was almost 200 meters deep and, at a point 70 meters above the floor, the valley was approximately 300 meters wide.

Cross-beds in the conglomeratic unit at the base of the White River Group sediments at Slim Buttes have been mapped by Malhotra and Teglund (1959) and indicate the river which deposited the material came from the northwest. A similar study by Halley (1986) in the Chalky Buttes-White Butte complex showed the river which deposited the conglomerate there flowed south-southeast.

The Yellowstone River history implied by the above evidence suggests the Yellowstone River has cut its valley as much as 400 meters since the earliest channels attributed here to glacial diversion. The age of these early Yellowstone channels can be debated. Fossils found in some of the early Yellowstone River channel sediments suggest an Oligocene age (Lillegraven, 1970, Douglas, 1909, Hoganson and Lammers, 1985, Kihm and Lammers, 1986). The erosion rates calculated in this paper present a strong argument for a much younger age. Also the behavior of the Yellowstone River presents a strong argument for glacial diversion. Climatic models based on oceanographic data suggest major continental ice sheets began on the North American continent about 3.2 million years ago (Shackleton and Opdyke, 1977). Accepted radiometric dates for these sediments are not available (Prothero, 1985). Resolution of these conflicting age dates may be possible by studying published erosion rates for the Yellowstone River and the northern Great Plains in general.

NORTHERN GREAT PLAINS EVIDENCE FOR EROSION RATES

Reheis and Agard (1984) have dated terrace gravels and calculated incision rates for the Yellowstone River near Billings, Montana. A terrace 295 meters above the present river was dated at 2.0 million years giving an incision rate of 0.15 meters per thousand years. Incision rates for Rock Creek, a tributary of the Yellowstone near Billings, were calculated at 0.12 meters per thousand years. These incision rates suggest the Yellowstone River has cut down over 400 meters in the past three million years.

Two hundred kilometers downstream on the Yellowstone River from Billings, Montana, Colton, Naesar and Naesar (1986) have determined a maximum date of seven million years ago for the Rimroad gravels south of Circle, Montana. The high-level Rimroad gravels are approximately 400 meters above the modern Yellowstone River. The seven million year date probably is a limiting date and the gravels may be much younger. However, even if the gravels are close to seven million years old, the incision rate for the river suggests almost 200 meters of downcutting in the past three million years. In addition Colton, Naesar and Naesar indicate the Yellowstone River has migrated 56 kilometers to the southeast since desposition of the Rimroad Gravel.

Colton, Naesar and Naesar (1986) also report a ten million year date for zircons from ash deposits underlain by sand and gravel in the Flaxville Formation of eastern Montana. The sand and gravel was probably deposited by the ancestral Missouri River at a time when it flowed 80 kilometers north of the present Missouri River and some 365 meters higher than the floor of the modern Missouri. Again the ten million year date is probably a limiting date and the sand and gravel may be much younger. Even if we assume the ten million year date is close to correct, however, the Missouri River appears to have cut down over 100 meters in the past three million years.

Gates and Rahn (1986) in a study of ancient quartzite boulders in the Red Valley area of the northern Black Hills of South Dakota and Wyoming suggest those boulders have been let down as much as 300 meters in elevation during the later part of the Cenozoic era. They suggest the region north of the Black Hills has experienced 300 meters of erosion during the past three million years.

The estimated amount of downcutting for the northern Great Plains region discussed in this paper are summarized in Table 1. The incision rates for major rivers range from a high of over 400 meters in the past three million years to a low of approximately 100 meters during the same time period. Most of the erosion rates in Table 1 are based on limiting dates and the more rapid incision rates may be much closer to being correct than the lower incision rates.

Table 1. Estimates of erosion in the northern Great Plains during the past three million years.

Source of data	Location	Workers	Erosion Estimate
Yellowstone River	Billings, Montana	Reheis and Agard, 1984	400 plus meters
Yellowstone River	Circle, Montana	Colton, Naesar and Naesar, 1986	200 plus meters
Missouri River	Flaxville Plain, Montana	Colton, Naesar and Naesar, 1986	100 plus meters
Northern Black Hills	South Dakota and Wyoming	Gates and Rahn, 1986	300 meters
Continental margins	North America	Bell and Lazar, 1985	120 plus meters
Glacial erratics	Southwest North Dakota	Clayton, 1969	60 plus meters

CONCLUSIONS

There is strong evidence for deep erosion of the Williston Basin region during the late Cenozoic. The evidence includes a major erosion surface which cuts across numerous stratigraphic units. Incision rates calculated for major rivers which cross the Williston Basin region suggest as much as 400 meters of sediments have been removed from the region in the past three million years. The late Cenozoic erosion surface was probably produced by the erosive actions resulting from some 25 major glacial episodes which affected the northern Great Plains. Erosion was probably accomplished both by the ice and by the tremendous volumes of meltwater which repeatedly attacked the soft claystone bedrock of the Williston Basin region.

Evidence for these multiple glaciations and the progressive downcutting by major rivers can be observed in western North Dakota and northwestern South Dakota today. Sediments which appear to represent former channels of the Yellowstone River can be found along the drainage divide between the north-flowing Little Missouri River and the southeast-flowing Heart, Cannonball, Grand and Moreau rivers. Apparently the Yellowstone River was repeatedly diverted to the southeast by continental ice sheets.

Additional evidence for the deep glacial erosion of the Williston Basin region is found in what appear to be remnants of a complex system of extremely wide and shallow glacial through valleys. Escarpments which form the walls of these hypothesized glacial through valleys are the major topographic features of the northern Great Plains region today. Glacial erosion of the northern Great Plains region probably increased to the northeast. The present-day northeast slope in North Dakota probably developed in response to this deep erosion.

REFERENCES CITED

Bell, M. and Laine, E.P., 1985, Erosion of the Laurentide region of North America by Glacial and glacio-fluvial processes: Quaternary Research, v. 23, p. 154-174.

Bluemle, J.P., 1978, The Face of North Dakota-The Geologic Story: North Dakota Geological Survey Educational Series, no. 11, 75 p.

Carlson, C.G., 1969, Bedrock Geologic Map of North Dakota (Scale 1:1,000,000): North Dakota Geological Survey Miscellaneous Map 10, Grand Forks, North Dakota.

Chumakov, N.M., 1973, Continental ice sheets and Precambrian shields: Geological Society of America Bulletin, v. 84, p. 1839-1840.

Clayton, Lee, 1969, Preliminary geologic map of Dunn County, North Dakota: North Dakota Geological Survey Miscellaneous Map 11, Grand Forks, North Dakota.

Clayton Lee, 1980, Geologic Map of North Dakota (Scale 1:500,000): United States Geological Survey, Denver, Colorado.

Clayton, L., Moran, S., and Bluemle, J., 1980, Explanatory text to accompany the Geologic Map of North Dakota: North Dakota Geologic Survey Report of Investigation no. 69, 93 p.

Colton, R.B., Naesar, N.D. and Naeser, C.W., 1986, Drainage changes in eastern Montana and western North Dakota during Late Cenozoic time: Abstracts with Programs 1986: 39th Annual Meeting, Rocky Mountain Section, The Geological Society of America, p. 347.

Douglas, Earl, 1909, A geological reconnaissance in North Dakota, Montana, and Idaho; with notes on Mesozoic and Cenozoic geology: Carnegie Museum Annals, v. 5, p. 211-288.

Erickson, A.K., 1970, Surficial lineaments and their structural implications in the Williston Basin: Unpublished Master's Thesis, University of North Dakota, 59 p.

Flint, R.F., 1955, Pleistocene Geology of Eastern South Dakota: United States Geological Survey Professional Paper 262, 173 p.

Gates, W.C.B., and Rahn, P.H., 1986, Ancient quartzite boulders in the Red Valley areas of northern Black Hills, South Dakota and Wyoming: Mountain Geologist, v. 23, p. 95-97.

Gill, J., 1962, Tertiary landslides, northwestern South Dakota and southeastern Montana: Geological Society of America Bulletin, v. 73, p. 725-736.

Gravenor, C.P., 1975, Erosion by continental ice sheets: American Journal of Science, v. 275, p. 594-604.

Halley, LaVonne, 1986, The conglomeratic unit of the White River Group, Chalky Buttes, Slope County, North Dakota: Proceedings of the North Dakota Academy of Science, v. 40, p. 129.

Hays, J.D., Imbrie, J. and Shackleton, N.J., 1976, Variations in the earth's orbit: pacemaker of the ice ages: Science, v. 194, p. 1121-1132.

Hoganson, J.W., and Lammers, G.E., 1985, The vertebrate fauna and paleoecology of the Dickinson member, Brule Formation (Oligocene) in Stark County, North Dakota: Proceedings of the North Dakota Academy of Science, v. 39, p. 15.

Imbrie, J., and Imbrie, K.P., 1979, Ice Ages: Solving the Mystery: Enslow Publishers, Short Hills, New Jersey, 224 p.

Kihm, A.J., and Lammers, G.E., 1986, Vertebrate biochronology of Oligocene sediments in southwest North Dakota: Proceedings of the North Dakota Academy of Science, v. 40, p. 18.

Lemke, R.W., 1960, Stratigraphy, structure, and vertebrate fossils of the Oligocene Brule Formation, Slim Buttes, Northwestern South Dakota: Geological Society of America Bulletin, v. 81, p. 831-850.

Malhotra, C.L. and Teglund, E.R., 1959, A new Tertiary formation in Harding County, South Dakota: Proceedings of the South Dakota Academy of Science, v. 38, p. 263-274.

Montagne, J.M., 1972, Wisconsin glaciation: in Geologic Atlas of the Rocky Mountain Region: United States of America (W.W. Mallory et al. eds.), Rocky Mountain Association of Geologists, Denver, p. 257-261.

Prothero, D.R., 1985, Correlation of the White River Group by magnetostratigraphy: Dakoterra, v. 2, p. 265-276.

Reheis, M.C., and Agard, S.S., 1984, Timing of stream captures in the Bighorn Basin, Wy. and Mt., determined from ash dated gravels: Abstracts with Programs 1984, Geological Society of America 97th Annual Meeting, p. 632.

Shackleton, N.J. and Opdyke, N.D., 1977, Oxygen isotope and paleomagnetic evidence for early Northern Hemisphere glaciation. Nature, v. 270, p. 216-219.

Sugden, D.E., 1976, A case against deep erosion of shields by ice sheets: Geology, v. 4, p. 580-582.

Thornbury, W.D., 1965, Regional Geomorphology of the United States: John Wiley & Sons, New York, 609 p.

Todd, James E., 1914, The Pleistocene history of the Missouri River: Science, n.s., v. 39, no. 995, p. 263-274.

Toepelman, W.C., 1925, The geology of a portion of the Slim Buttes region of northwestern South Dakota with special reference to unusual features due to slumping: Unpublished PhD thesis, Univ. Chicago, Chicago, Illinois. 245 p.

White, W.A., 1972, Deep erosion by continental ice sheets: Geological Society of America Bulletin: v. 83, p. 1037-1056.

A GEOLOGIC AND ECONOMIC APPRAISAL OF THE OIL POTENTIAL OF THE WILLISTON BASIN (ABSTRACT)

A. H. JENNINGS

2156 So. Field St.
Lakewood, CO 80227

A geologic and economic appraisal was made of the oil potential of the Williston Basin of Montana, North Dakota and South Dakota. The major producing intervals investigated were the Ordovician, Devonian and Mississippian.

Data for the appraisal came from field and drilling statistics and geologic studies of more than eighty producing oil fields.

An extrapolated oil production decline curve was first constructed for a theoretical "average" producing well for each field. From this an estimated economic return was calculated which included cost of drilling and discounting for royalty, taxes, etc. No considerations were made for exploration and land acquisition costs.

The estimated returns, after posting on Williston Basin geologic maps, showed the relative geologic and economic factors of the major Ordovician, Devonian and Mississippian production within the basin and where the best economic returns might be expected.

Ordovician: The best present-day economic returns, ranging from $2.50 to $3.50 per dollar invested, are found on the northwestern flank of the basin in Sheridan and Roosevelt Counties, Montana. Traps in this area are generally small structural closures with stratigraphic help from secondary dolomitization. Fairly deep drilling depths of 10,000 to 12,500 feet, however, are detrimental to the economics. Multiple pay potential, on the other hand, is a favorable factor for the area.

Devonian: The best economic returns of $9.00 to $15.00 per dollar invested are present in the extreme northwestern portion of the basin in Roosevelt County, Montana. Traps here are structural closures resulting from differential solution of the Devonian Prairie salt. Drilling depths are moderate ranging from 7000 to 8000 feet.

Mississippian: This is the most rewarding production in the Williston Basin. Returns of $10.00 to $20.00 per invested dollar can be made in the northeastern portion in Renville, Bottineau and Ward Counties, North Dakota. Traps in this region are primarily stratigraphic pinchouts or truncations with an occasional structural assist. Pay depth is less than 5000 feet which is a very favorable economic factor.

GEOLOGY OF THE INDIAN HILL FIELD AREA, CENTRAL WILLISTON BASIN, NORTH DAKOTA — A MULTIPLE-PAY FIELD DEVELOPED IN THE 1980s

JERROLD D. MAYER

Apache Corporation
Suite 4900 One, United Bank Center
1700 Lincoln Street
Denver, Colorado 80203

ABSTRACT

The Indian Hill Field area (which includes Hardscrabble Field and a portion of Camp Field) is located on a southeast plunging anticline in northwestern McKenzie County and southwestern Williams County, North Dakota. Production was established in 1978 followed by the addition of 5 shallower producing zones in the early 1980s. The productive area is approximately 10 miles long and up to 3.5 miles wide with production from Paleozoic carbonate reservoirs. The primary objectives are Ordovocian Red River, Silurian Stonewall, Devonian Duperow, and Mississippian Mission Canyon; and the secondary objectives are Devonian Nisku and Mississippian Ratcliffe. Productivity and reservoir development are highly variable. In general, the Red River "D" zone and the Duperow produce along the flanks of the structure whereas the Red River "C" and "B" zones, the Stonewall, and the better Mission Canyon produce from the crest of the structure. Cumulative production through December 1986 is 8.6 MMBO.

INTRODUCTION

The Indian Hill Field study area is located in northwestern McKenzie County and southwestern Williams County, North Dakota, in the central portion of the Williston Basin, approximately 8 miles south-southwest of the town of Williston. An index map shows the location of the study area with respect to major geographic and structural features, as well as to significant productive areas (Fig. 1).

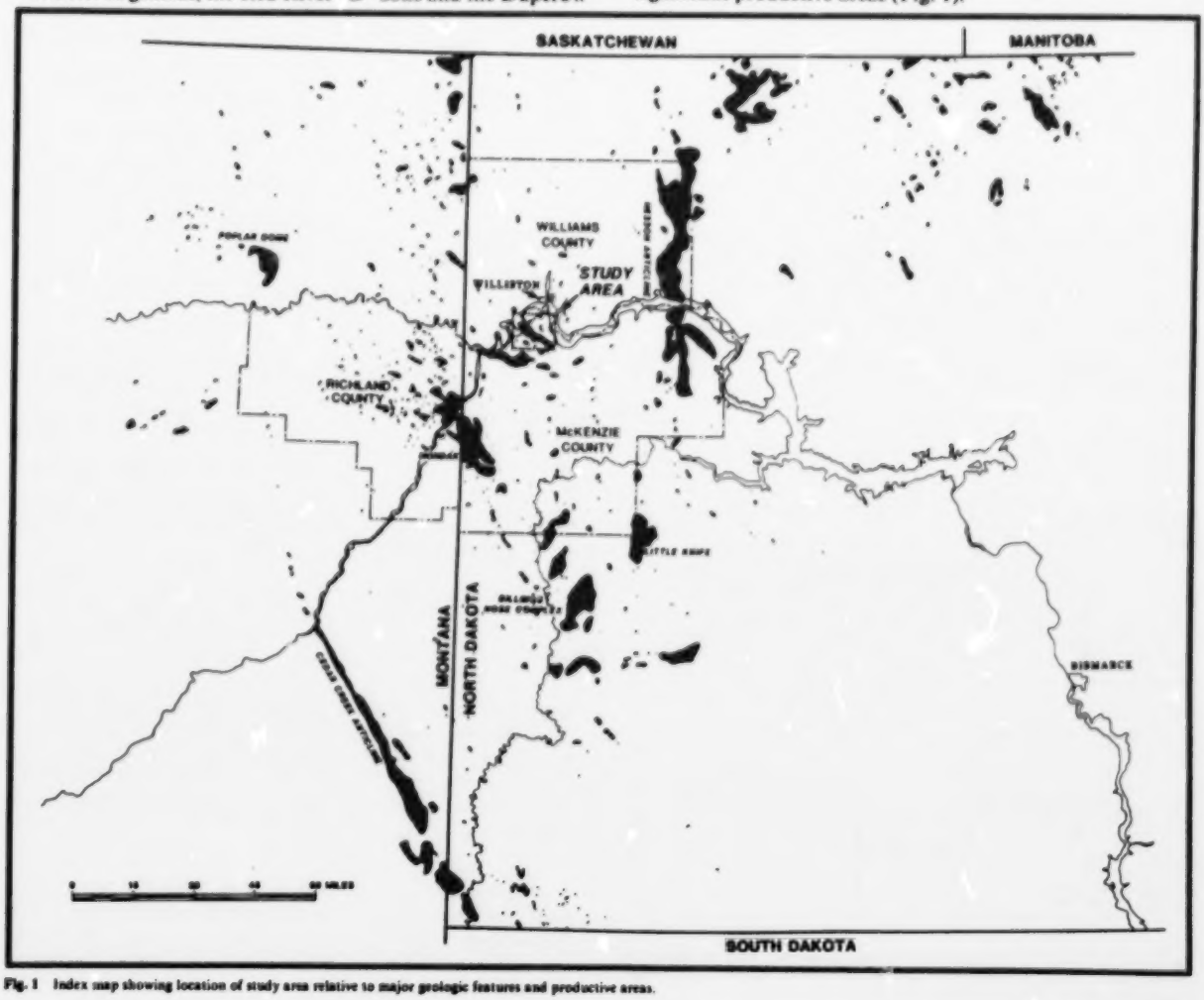


Fig. 1 Index map showing location of study area relative to major geologic features and productive areas.

Indian Hill Field is located on a northwest to southeast plunging anticline which includes Hardscrabble Field to the northwest and Camp Field to the southeast (Fig. 2). Hardscrabble Field and a portion of Camp Field are included in the Indian Hill Field study area because they are situated on the same continuous structure. Several wells from Camp Field (4 Mission Canyon, 1 Stonewall, and 2 Red River) that are not on the main structure are not included. The Indian Hill Field area has proven production from six Paleozoic carbonate reservoirs: Ordovician Red River, Silurian Stonewall, Devonian Duperow and Nisku, and Mississippian Mission Canyon and Ratcliffe Formations (Fig. 3).

The discovery well for Indian Hill Field, the Mosbacher-Pruet FLB 26-1 (NE NW 26-T153N-R101W) was completed for 588 BOPD from Red River in December 1978. Multiple-pay production was established when Gulf recompleted the Eckert Foundation 1 in NE SE 6-T152N-R101W in September 1982 for 305 BOPD from the Mission Canyon. As of December 1986, the field study area consists of the following wells: 1 Ratcliffe, 60 Mission Canyon (plus 1 shut-in and 1 recompleted), 3 Nisku (plus 1 recompleted), 9 Duperow (plus 2 recompleted), 5 Stonewall (plus 2 recompleted) and 10 Red River (plus 2 abandoned and 4 recompleted). Cumulative production through December 1986 is approximately 8.5 MMBO; daily production is 5874 BO.

This paper will discuss the structural and stratigraphic control of hydrocarbon production of the four primary producing formations in the field area: the Red River, Stonewall, Duperow, and Mission Canyon.

DEVELOPMENT HISTORY

Indian Hill Field was discovered in December 1978 by the Mosbacher-Pruet FLB 26-1 (NE NW 26-T153N-R101W) that was completed for 588 BOPD from Red River. The discovery was successfully offset to the north and south, in SW SE 23-T153N-R101W and NE SE 26-T153N-R101W, and unsuccessfully offset to the west in SE NE 27-T153N-R101W. Red River production was further extended by: the Gulf Eckert Foundation 1 (NE SE 6-T152N-R101W) flowing 190 BOPD, 21 BWPD in May 1979; the Hardscrabble Field discovery, the Gulf Skurdal 1-24-3B (NE SE 24-T153N-R102W) flowing 254 BODP, 18 BWPD in June 1982; and the Camp Field discovery, the Pogo Schmitz 1-9 (NW SW 9-T152N-R101W) which was completed in July 1982 pumping 58 BOPD, 24 BWPD (Fig. 2).

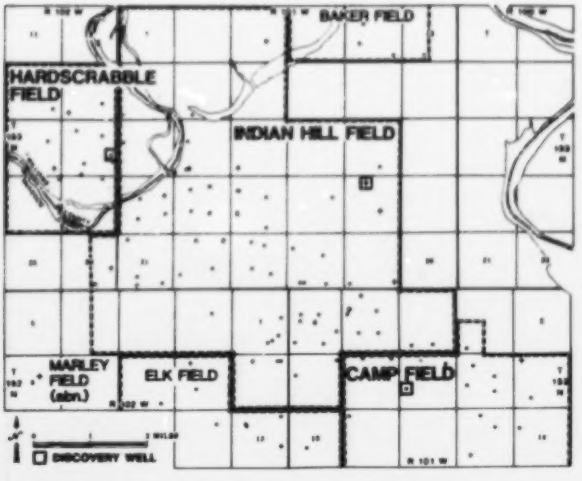


Fig. 2 Index map showing field outlines and well locations included within and adjacent to the study area. Well data from Baker, Elk, and Marley Fields are included in the geologic mapping but not in the discussions in this report.

PERIOD	SEQUENCE	FORMATION		APPROX. DEPTH
MISSISSIPPIAN	KASKASKIA	OTTER		7850'
		KIBBEY		8040'
		MADISON GROUP	CHARLES	8200'
			RATCLIFFE ●	9090'
			MIDALE	9200'
			MISSION CANYON ●	9240'
			LODGEPOLE	9980'
DEVONIAN		BAKKEN		10,510'
		THREE FORKS		10,570'
		NISKU ●		10,780'
		DUPEROW ●		10,870'
		SOURIS RIVER		11,310'
		DAWSON BAY		11,550'
		PRAIRIE		11,670'
		WINNIPEGOSIS		11,900'
		ASHERN		12,130'
SILURIAN	TIPPECANOE	INTERLAKE		12,150'
		STONEWALL ●		12,290'
ORDOVICIAN		GUNTON		13,020'
		STONY MTN.		13,120'
		RED RIVER ●		13,180'
		WINNIPEG GP.		13,740'

● PRIMARY OBJECTIVE

● SECONDARY OBJECTIVE

Fig. 3 Generalized stratigraphic column for Mississippian through Ordovician periods with approximate depth in study area.

A switch in emphasis from Red River to Mission Canyon began in September 1982 when Gulf recompleted the Eckert Foundation 1 (NE SE 6-T152N-R101W), flowing 305 BOPD. An earlier drillstem test of the productive interval recovered 651' G&O plus 701' G&OCM.

Further evidence of the multiple-pay potential of the area was proven as drilling continued. Stonewall production was established by the Superior Nelson 2 (SW SE 1-T152N-R102W), completed flowing 325 BOPD in August 1982. Economic Duperow potential was indicated in the Cotton Fjelstad 1-6 (SW NW 6-T152N-R101W) which recovered 3692'(52.6 bbl) O, 982'(9.7 bbl) SW during a three-hour DST in July 1983; and was first produced from the Superior Nelson 2-2 (SW SE 1-T152N-R102W), pumping 203 BOFD, 82 BWPD in June 1984. Oil from Nisku was drillstem tested from several wells, including the Gulf Eckert Foundation 1 (NE SE 6-T152N-R101W), the Cotton Devitt 2-29 (NW SE 29-T153N-R101W); and was first completed in the Columbia Gas Kelter 28-1 (SW NE 28-T153N-R101W) which had an IPP of 50 BOPD. This well was subsequently recompleted in the Mission Canyon. A drillstem test in December 1983 was the first indication of Ratcliffe potential in the field: the Cotton Devitt 2-29 (NW SE 29-T153N-R101W) recovered 705' HGCM&O, 100' HGCM. Ratcliffe production was established in December 1985 by the Tenneco Schmidt 2-25 (NE NW 25-T153N-R102W) pumping 151 BOPD, 70 BWPD.

GENERAL GEOLOGY

This paper will present generalized concepts about the geology of the Indian Hill Field area as it relates to hydrocarbon occurrences. Discussions of geologic history pertinent to this study area have been published by Porter and Fuller (1959), Sloss (1963), Carlson and Anderson (1966), and — more recently — Gerhard et al (1982).

The shallow-marine sedimentation which dominated the Williston Basin throughout Paleozoic time resulted in deposition of repeated transgressive-regressive carbonate/evaporite sequences. The Indian Hill Field area currently produces from carbonate rocks which range from Ordovician to Mississippian in age and which are included in the Tippecanoe and Kaskaskia sequences (Fig. 3). The basic stratigraphic sequence of alternating limestone, dolomite, and anhydrite was repeated in complete or partial cycles throughout the Paleozoic (approximately 120-150 million years) and laterally throughout most of the Williston Basin. These cycles have been variously interpreted as both "shallowing-upward" (Wilson, 1975; Carroll, 1979; Altschuld and Kerr, 1982; Clement, 1985; Derby and Kilpatrick, 1985; and Ruzyla and Friedman, 1985), and as "brining-upwards" (Kendall, 1976; Kohm and Louden, 1978; and Longman et al, 1983).

Reservoir development in carbonate rocks typical of the Indian Hill Field area consists of primary and secondary porosity. Primary porosity in these carbonate rocks is generally formed in higher energy (shoaling) environments as skeletal-rich to oolitic-pisolitic packstone, grainstone, or boundstone. This is the "Y" facies described by Irwin (1965) as being the most likely facies to develop primary porosity.

Secondary porosity is formed predominantly by dolomitization, with contributions by leaching of anhydrite and calcium carbonate (Lindsay and Roth, 1982). Dolomitization, by whatever model is most likely, will be more pervasive in the more permeable beds which would act as conduits for the dolomitizing fluids, assuming no mineralogic or other variables (Carroll, 1979; Davies, 1979; Altschuld and Kerr, 1982; Burke and Stefanovsky, 1982; Gerhard et al, 1982; Longman et al, 1983; and Clement, 1985).

Davies (1979) stated that earlier work by Wilson (1975), Dunham and Olson (1978), and others had shown the correlation between rock facies (primary porosity) and dolomitization, and the common tectonic control for both parameters. That is, sites favorable for primary porosity are more likely to occur on or near paleohighs where there is also an increased likelihood for dolomitization (secondary porosity). If there is a repetition of this favorable depositional/diagenetic setting (shoaling/dolomitization) in the same area throughout time, this may result in a "stacking" of multiple reservoirs on basement controlled positive features. The fact that favorable reservoir development occurs in the same area throughout time is evidence of recurrent movement on a basement structural element. Recurrent movement may also create fracture enhancement of the reservoir (Murray, 1968; Byrd, 1978; Lindsay and Roth, 1982; Parker and Powe, 1982).

The Indian Hill Field area produces from six separate formations and is an example of an area with "stacked" or multiple pays (Fig. 3). The four primary producing formations — the Ordovician Red River, Silurian Stonewall, Devonian Duperow, and Mississippian Mission Canyon — are presented in further detail.

RED RIVER

STRUCTURE

Red River structure in the Indian Hill Field area strikes approximately north-south and dips regionally to the east at a rate of 50-100 feet per mile (Fig. 4) Current subsurface control indicates three areas of structural closure as mapped with a 50 ft contour interval. Two of the closures, located in Sec. 6-T152N-R101W and Sec. 12-T152N-R102W, are approximately 0.5 to 1 mile in diameter which is typical for this portion of the basin, according to the author's regional mapping. This is also consistent with the findings of Kohm and Louden (1978) and Longman et al (1983) in their studies in nearby Richland County, Montana. By contrast, a much larger closure has been identified, centered in N/2 Sec 29-T153N-R101W, which is approximately 3.5 miles long perpendicular to strike and 2.1 miles wide parallel to strike, with a minimum of 38 ft of closure. This structure is slightly asymmetric with a steeper north flank. It should be noted that recent re-survey information supplied to the author resulted in correcting the kelly

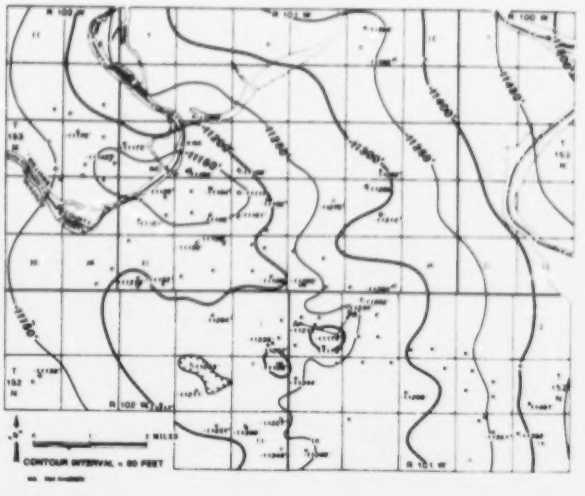


Fig. 4 Ordovician Red River Formation structure map. Location of the Red River cross-section is indicated by the dashed line A-A'. Well spots without datums do not penetrate the Red River Formation.

bushings for the wells in the NW and SE of Sec 26-T153N-R101W by -50 ft and -61 ft respectively. These corrections have been used for all structural interpretations in this report.

STRATIGRAPHY

Previously published works concerning the stratigraphy (and hydrocarbon occurrences) of the Red River Formation include Ballard (1969), Walsh (1969), Kendall 1976), Asquith et al (1978), Kohm and Louden (1978), Carroll (1979), Wittstrom and Chimney (1980), Gerhard et al (1982), Parker and Powe (1982), Longman et al (1983), Kendall (1984), Clement (1985), Derby and Kilpatrick (1985), and Ruzyla and Friedman (1985).

The Red River in the Indian Hill Field area has been informally divided into 4 main zones, the "A", "B", "C", and "D". These zones were further subdivided into the "A" anhydrite, "A" dolomite, "A" limestone, "B" anhydrite, "B" laminated, "B" burrowed, "C" anhydrite, "C" laminated, "C" burrowed, and "D" zones (Fig. 5). These descriptive correlations are interpretations of cyclic layers of limestone, dolomite, and anhydrite based on the work of Kohm and Louden (1978), Carroll (1979), and Longman et al (1983). Deposition occurred either as a regressive sequence of subtidal-intertidal-supratidal facies (Asquith et al, 1978; Carroll, 1979; Wittstrom and Chimney, 1980; Gerhard et al, 1982; Clement, 1985; Derby and Kilpatrick, 1985; and Ruzyla and Friedman, 1985), or as a "brining-upward" subtidal depositional cycle (Kendall, 1976; Kohm and Louden, 1978; Longman et al, 1983; and others).

In the Indian Hill Field area, the Red River has been cored in 2 wells with interpretations available for this report. The "B" anhydrite and "B" laminated zones (core interval 13,053'-72') were cored in the Columbia Gas Deer Pass 20-1in SW SW 20-T153N-R101W. The depositional environment was interpreted as fluctuating shallow subtidal to supratidal on a shallow carbonate platform (John Santos, geologist, Columbia Gas Dev. Corp., personal communication, April 1986). The lower "C" burrowed and upper "D" zones (core interval 13,494'-545') were cored in the Cotton 1-2 Fredrickson in SW NE 2-T152N-R102W. The depositional environments of this interval were interpreted to be alternating subtidal to intertidal with some supratidal. Evidence for intertidal to supratidal deposition included features interpreted as dessication cracks and subaerial hardgrounds.

Porosity in the Red River of the Indian Hill Field area is restricted to dolomitized portions of the "A" dolomite, "B" laminated, "C" laminated, "C" burrowed, and "D" zones and is inferred to be entirely secondary in origin.

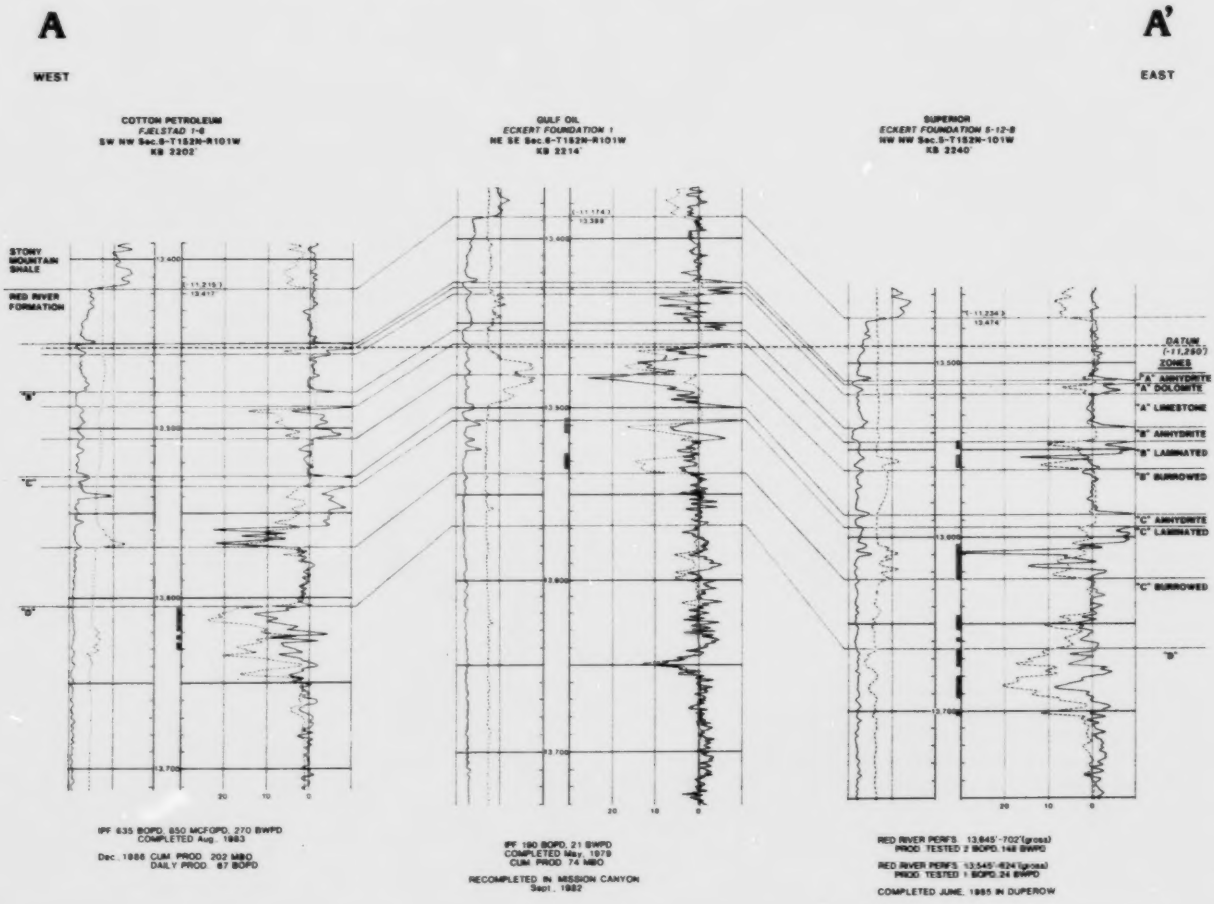


Fig. 5 Ordovician Red River Formation structural cross-section, FDC-CNL logs. Refer to Fig. 4 for line of section.

RESERVOIR DEVELOPMENT AND PRODUCTION DATA

In the Indian Hill Field area, the Red River produces from the "B" laminated, "C" laminated, and "D" zones (Figs. 5, 6). In general, the "B" and "C" produce from around the flanks, supporting the conclusions of Carroll (1979). The "D" zone reservoir is the thickest and most prolific Red River zone in the Indian Hill Field area (Table 1). This confirms the ideas of Wittstrom and Chimney (1980) who stated that porosity of reservoir quality is more likely to be developed around the perimeter than on the crest of Ordovician structures. This model is based on the thesis that lower nucleation rates for dolomite, caused by a lower Mg/Ca ratio as the dolomitizing fluid percolates downdip from the crests of the topographic highs, are more favorable for the formation of sucrosic dolomite with porosity.

The "down-dip "D" zone" concept was used successfully in drilling the Cotton Fjelstad 1-6 (SW NW 6-T152N-R101W) finding 36 ft of porosity greater than 5 per cent FDC-CNL in the "D" zone and 41 ft low to the Gulf Eckert Foundation 1 (NE SE 6-T152N-R101W) which had no equivalent "D" zone porosity (Fig. 5). Cumulative production of the Fjelstad 1-6 is 202 MBO as of December 1986.

However, not all the "D" zone porosity in favorable structural positions is productive. Core analysis from the Cotton Fredrickson 1-2 (SW NE 2-T152N-R102W) indicates that the permeability of the reservoir can be adversely affected by poorly connected pore throats, accumulations of bituminous material, and small crystal size. The Fredrickson 1-2 is located approximately 1.5 miles west and 9 ft structurally high to the Fjelstad 1-6. It has approximately 24 ft of porosity greater than 10 per cent FDC-CNL in the "D" zone plus 24 ft in the "C" laminated and "C" burrowed zones which drillstem tested approximately 1000' G&MCSW with a calculated permeability 0.22 md. Measured permeability from core analysis averaged approximately .76 md (range less than 0.1 to 5.6 md; two fractured samples were eliminated). Permeability problems such as these may explain the lack of productivity of a number of wells (and different formations) which have favorable structural positions, log calculations, and hydrocarbon shows.

Red River production, as of December 1986, is 940 BOPD from 10 wells; cumulative production is 1,593 MBO (plus 6 recompleted or abandoned wells) (Table 1).

Table 1. Red River Production Data, Indian Hill Field Area.

Well Name Location	Productive Zone	Gross Porosity Thickness (1)	Initial Potential BOPD Date	Cum. Prod. MBO (Dec 1986)	Current Prod. BOPD (Dec 1986)
Sturdal 1-24-30 NE SE 24-153-102	D	24	254 June 1982	283	113
Deer Pass 20-1 SW SW 20-153-101	D	27	623 Mar 1984	278	188
Elk 29-1 NW SW 29-153-101	B/C	11/24	362 July 1983	215	129
FLA 1-26 NE NW 26-153-101	D	30	588 Dec 1978	215	abn
Fjelstad 1-6 SW SW 6-152-101	D	36	635 Aug 1981	202	67
Eckert Foundation 5-6 SW SE 6-152-101	C	19	298 May 1984	79	60
Eckert Foundation 1 NE SE 6-152-101	C	14	190 May 1979	74	recomp
Nelson 1 NE NE 12-152-102	C	20	88 Dec 1981	52	45
Schmitz 1-9 NW SW 9-152-101	C	26	58 July 1982	52	15
Possum 34-1 SW SW 34-153-101	D (2)	26	100 Sept 1983	31	11
Dahl 23-1 SW SE 23-153-101	C	14	119 Oct 1980	28	recomp
Possum 26-1 NW SE 26-153-101	D	14	37 Jan 1980	28	abn
Mor Corp 29-2 NW NE 29-153-101	B/C	9/4	261 Sept 1983	19	recomp
State 1-19 SE SE 19-153-101	C/D	12/23	837 Oct 1986	16	189
Wegley 20-1 SW NW 20-153-101	(3)		204 Sept 1986	11	123
Kelter 28-1 SW NE 28-153-101	B/C	15/11	100 Mar 1983	10	recomp

(1) Total thickness in feet of porosity in zone greater than 5% FDC-CNL log. Purpose borehole may affect accuracy of logs.
(2) Open hole completion. Other zones may be contributing production.
(3) Not available

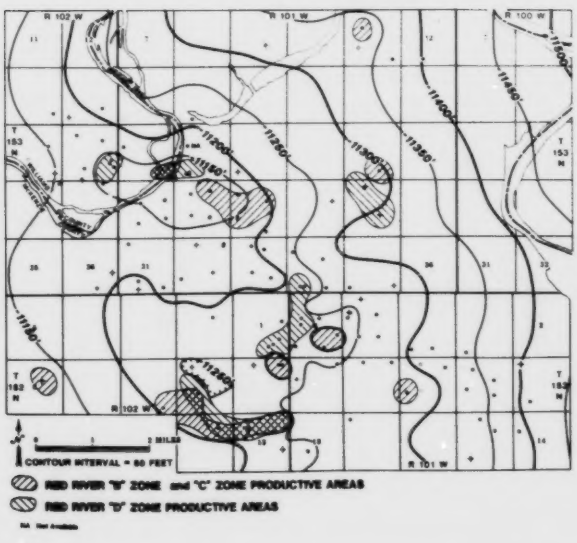

R 102 W
R 101 W
R 100 W
T 153 N
T 152 N
CONTOUR INTERVAL = 50 FEET
RED RIVER "B" ZONE and "C" ZONE PRODUCTIVE AREAS
RED RIVER "D" ZONE PRODUCTIVE AREAS

Fig. 6 Ordovician Red River Formation productive areas keyed by zone. Refer to Table 1 for production data on individual well basis.

STONEWALL

STRUCTURE

The regional strike of the Stonewall structure is northeast-southwest with the plunge of the overall Indian Hill anticline to the southeast (Fig. 7). This is the dominant structural configuration of the field area which persists on all younger mapped horizons. Current subsurface control mapped with a 25 ft contour interval indicates a similar size and configuration to that of the underlying Red River structure. The larger structure, centered in SW Sec 20-T153N-R101W, has a minimum closure of 35 ft. The size of this feature is approximately 4 miles long and 2.5 miles wide with a slightly steeper north flank. Two smaller closures approximately 0.5 to 1 mile in diameter are located in Sec 6-T152N-R101W and Sections 1 and 12-T152N-R102W.

STRATIGRAPHY

Little has been published specifically on the Stonewall Formation although Porter and Fuller (1959), Roehl (1967), and Kendall (1976) discuss this interval in their reports. In identifying the Stonewall, this paper follows the correlations of Bluemle et al (1980), while some operators include this interval in the lower Interlake.

In the Indian Hill Field area, the Stonewall consists of three lithologic units: a lower argillaceous to anhydritic limestone which may be dolomitic in part; a middle porous to anhydritic

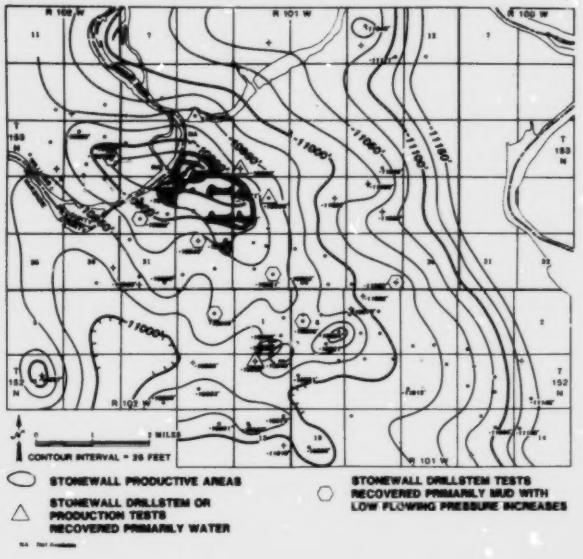

R 102 W
R 101 W
R 100 W
T 153 N
T 152 N
CONTOUR INTERVAL = 20 FEET
STONEWALL PRODUCTIVE AREAS
STONEWALL DRILLSTEM OR PRODUCTION TESTS RECOVERED PRIMARILY WATER
STONEWALL DRILLSTEM TESTS RECOVERED PRIMARILY MUD WITH LOW FLOWING PRESSURE INCREASES

Fig. 7 Silurian Stonewall Formation structure map. Well spots without datums do not penetrate the Stonewall Formation.

dolomite; and an upper anhydrite (Fig.8). Interpretations based on core (adjusted interval 12,844'-82') from the Columbia Gas Page 30-1 (SE NE 30-T153N-R101W) indicate that the porous middle dolomite interval (12,852'-74') is a skeletal wackestone-floatstone deposited in an open, shallow marine setting. The fauna includes echinoderms, corals, bryozoans, ostracods, brachiopods, gastropods, and molluscs. Above and below the porous interval are laminated and bioturbated, nonfossiliferous mudstones that locally contain sparse anhydrite nodules. Deposition in a shallow subtidal to intertidal environment is suggested. The mudstones are locally argillaceous and silty. The entire cored interval consists of dolomite but porosity is restricted to the skeletal wackestone-floatstone interval and is mostly intercrystalline, with minor amounts of moldic,intraskeletal, fracture, and vuggy porosity. However, the intercrystalline porosity in the Page 30-1 is discontinuous, contains dolospar cement, and bituminous residue which reduces the overall pore space and permeability of the reservoir.

Interpretations from a Stonewall core in the Columbia Gas Deer Pass 20-1 (SW SW 20-T153N-R101W) indicate a depositional sequence from shallow subtidal to supratidal (John Santos, geologist, Columbia Gas Dev. Corp., personal communication, May 1986). The overlying anhydrite is described as being massive and nodular.

It is interpreted that the middle unit skeletal wackestone-floatstone was deposited on a shallow marine bank coincident with or adjacent to paleotopographic highs. It is then inferred that the bank facies was preferentially dolomitized to form porosity which is coincident with or adjacent to the present-day Stonewall structural highs (Figs. 7, 9). The underlying non-porous limestone was probably deposited in a deeper water marine setting. Because some evidence exists for subaerial exposure in the mudstone above and below the porous middle interval and in the overlying anhydrite bed, this cycle of non-porous limestone, porous dolomite, and anhydrite is interpreted to have been deposited in progressively shallower water as a regressive sequence.

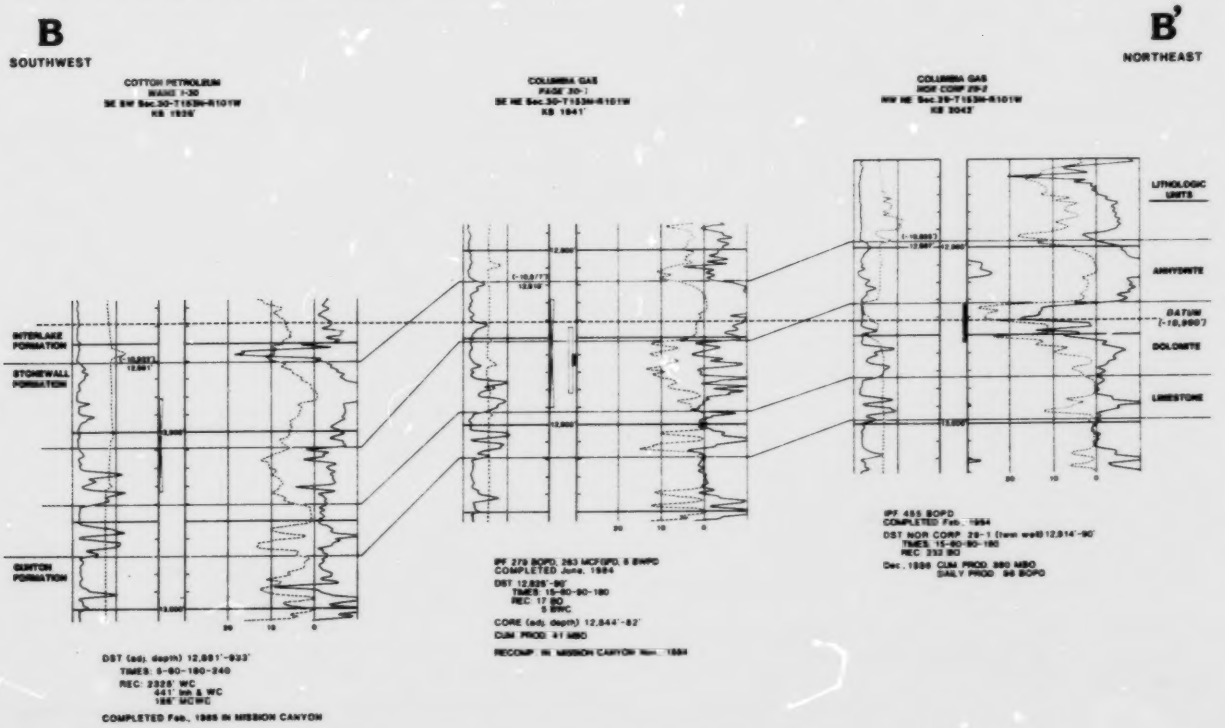


Fig. 8 Silurian Stonewall Formation structural cross-section, FDC-CNL logs. Refer to Fig. 9 for line of section.

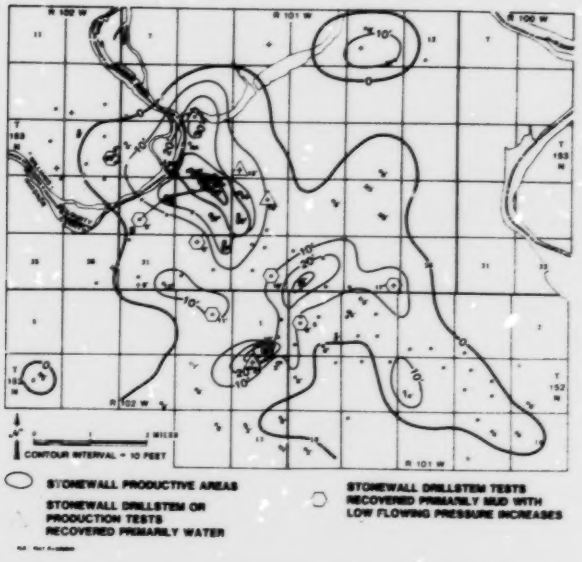

R 102 W
R 101 W
R 100 W
CONTOUR INTERVAL = 10 FEET
STONEWALL PRODUCTIVE AREAS
STONEWALL DRILLSTEM OR PRODUCTION TESTS RECOVERED PRIMARILY WATER
STONEWALL DRILLSTEM TESTS RECOVERED PRIMARILY MUD WITH LOW FLOWING PRESSURE INCREASES

Fig. 9 Silurian Stonewall Formation gross porosity isopach map. Porosity cut-off is greater than 4 per cent on FDC-CNL logs (rugose hole may affect accuracy of logs). Location of the Stonewall cross-section is indicated by the dashed line B-B'. Well spots without datums do not penetrate the Stonewall Formation.

RESERVOIR DEVELOPMENT AND PRODUCTION DATA

The majority of the Stonewall production in the Indian Hill Field area is centered in an area in Sections 20, 28, 29, 30, and 32-T153N-R101W. This productive area is restricted to a generally north-northwest to south-southeast trending porosity fairway (greater than 10 ft) which intercepts the structurally higher part of the field (Figs. 7, 9). Offstructure wells within the porosity fairway have tested wet and wells with less than 10 ft of porosity (FDC-CNL greater than 4 per cent) have drillstem tested as being tight. The Stonewall also produces from the Superior Nelson 2 (SW SE 1-T152N-R102W) where the porosity is developed in a northeast-southwest trending fairway on the northwest flank of the structure (Figs. 7, 9). Porosity thickness of the productive wells ranges from 13 ft to 32 ft (FDC-CNL greater than 4 per cent).

On a per well basis, the Stonewall is the most productive reservoir in the Indian Hill Field area (Table 2). The Columbia Gas Nor Corp 29-2 (NW NE 29-T153N-R101W) produced 360 MBO since February 1984 and was producing 96 BOPD in December 1986. An earlier drillstem test of the zone in the Nor Corp 29-1 (NW NE 29-T153N-R101W) produced approximately 232 BO in 105 minutes (Fig. 8). Cumulative Stonewall production for the Indian Hill Field area is 1,382 MBO from 5 wells (plus 2 recompleted wells) with daily production of 411 BOPD (December 1986 production data).

Table 2. Stonewall production data, Indian Hill Field area.

Well Name Location	Gross Porosity Thickness (1)	Initial Potential BOPD Date	Cum. Prod. MBO (Dec 1986)	Current Prod. BOPD (Dec 1986)
Nor Corp 29-2 NW NE 29-153-101	30	455 Feb 1984	360	96
Nelson 2 SW SE 1-152-102	32	325 Aug 1982	283	84
Rehab 28-1 SW NW 28-153-101	14	415 June 1984	273	74
Davitt 1-29 NW SE 29-153-101	17	915 Jan 1984	181	17
Davitt 1-32 NE NE 32-153-101	17	466 June 1984	172	140
Dear Pass 20-2 SE SW 20-153-101	24	332 Aug 1985	72	recomp
Page 30-1 SE NE 30-153-101	13	279 June 1984	41	recomp

(1) Total thickness in feet of porosity in zone greater than 4% FDC-CNL log. Rugose hole may affect accuracy of logs.

DUPEROW

STRUCTURE

The Duperow structure, aligned in an overall northwest to southeast trend, is broader with less vertical relief than the previously discussed deeper features (Fig. 10). The main structural closure, centered in SW Sec 20-T153N-R101W, has a minimum closure of 30 ft. and has an overall length of approximately 4.2 miles and width of approximately 2 miles. The smaller structures centered in Sec 6-T152N-R101W and Sec 1-T152N-R102W are mappable, but also with lesser amounts of closure.

STRATIGRAPHY

The Duperow of the Williston Basin has been previously described as consisting of a number of cycles of limestone, dolomite, and anhydrite deposited under regressive shallowing upward subtidal to supratidal conditions (Wilson, 1967; Hoganson, 1978; Altschuld and Kerr, 1982; Burke and Stefanovsky, 1982; and Pilatzke et al, 1985). Porosity is generally regarded to have been formed by the dolomitization of stromatoporid bioherms or banks and associated facies which were originally deposited in higher energy areas in a shallow subtidal environment.

In the Indian Hill Field area, the major Duperow producing interval is referred to as Zone 3 (Burke and Stevanovsky, 1982) or Cycle 3 because the pay zone is included in the third carbonate unit identified by bounding anhydrite beds beginning at the base of the Duperow (Fig. 11). This is the most common productive zone in the Duperow in the Williston Basin. Only

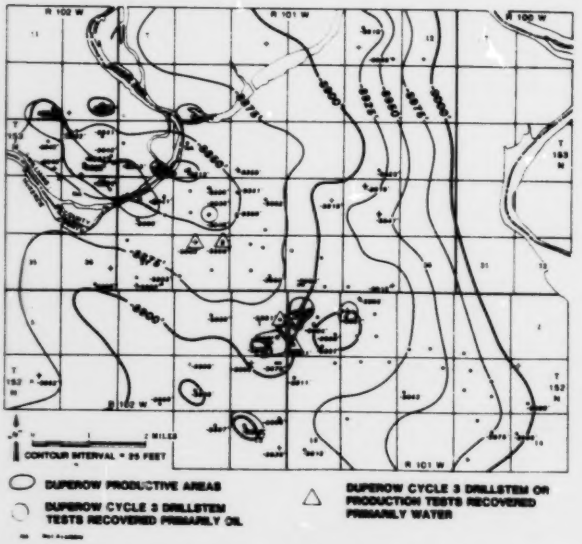

R 102 W
R 101 W
R 100 W
CONTOUR INTERVAL = 20 FEET
DUPEROW PRODUCTIVE AREAS
DUPEROW CYCLE 3 DRILLSTEM TESTS RECOVERED PRIMARILY OIL
DUPEROW CYCLE 3 DRILLSTEM OR PRODUCTION TESTS RECOVERED PRIMARILY WATER

Fig. 10 Devonian Duperow Formation structure map. Well spots without datums do not penetrate the Duperow Formation.

one well in the Indian Hill Field area, the Tenneco Erickson 4-25 (NE NE 25-T153N-R102W), has been perforated in additional Duperow zones.

The carbonate unit in Cycle 3 shows rapid lateral variations, from porous dolomite to tight limestone in wells located less than 2500 ft apart (Figs. 11, 12). Additionally at least one well, the Cotton Wang 1-30 (SE SW 30-T153N-R101W), appears by log analysis to have salt-plugged porosity thereby reducing the overall size and effectiveness of the reservoir. The author's examination of cuttings from wells in the Indian Hill Field indicate that the porosity is intercrystalline surosic dolomite which is inferred to be secondary in origin.

RESERVOIR DEVELOPMENT AND PRODUCTION DATA

Cycle 3 porosity in the Indian Hill Field area consists of a fairway which parallels and partially encircles the flanks of the structure (Figs. 10, 12). The northwest to southeast trending fairway along the southwestern flank of the structure is well defined. The extent of porosity in other areas is less certain due to lack of well control. Importantly, no significant porosity coincides with the highest part of the structure, which is centered in SW 20-T153N-R101W (Figs. 10, 12). This is also true of the structurally high wells in SE Sec 6-T152N-R101W. Assuming that the paleostructure was coincident with the present-day structure, it is possible that:

1) the depositional environment of the higher portion of the paleostructure was not as favorable to the growth of the stromatoporid bioherms,
2) dolomitization was not as pervasive on the top of the paleostructure,
3) the porous dolomite was reduced by later cementation, or
4) any combination of the above 3 factors.

The Duperow produces from several areas along the porosity fairway (Fig. 12). The productive wells have gross porosity thickness ranging from 2 ft to 15 ft (FDC-CNL greater than 10 per cent), with one exception (Table 3). As of December 1986, there were 9 wells producing 1090 BOPD with cumulative production of 683 MBO from the Duperow (including 2 recompleted wells).

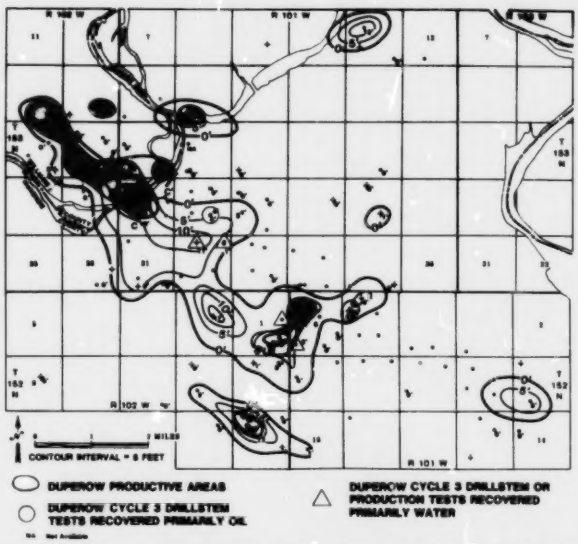

CONTOUR INTERVAL = 5 FEET
DUPEROW PRODUCTIVE AREAS
DUPEROW CYCLE 3 DRILLSTEM TESTS RECOVERED PRIMARILY OIL
DUPEROW CYCLE 3 DRILLSTEM OR PRODUCTION TESTS RECOVERED PRIMARILY WATER

Fig. 12 Devonian Duperow Formation 3rd Cycle gross porosity isopach map. Porosity cut-off is greater than 10 per cent on FDC-CNL logs (rugose hole may affect accuracy of logs). Location of the Duperow cross-section is indicated by the dashed line C-C'. Well spots without datums do not penetrate the Duperow Formation.

MISSION CANYON

STRUCTURE

The overall northwest to southeast Mission Canyon anticline is approximately 10 miles long and up to 3.5 miles wide (Fig. 13) Several closures mapped with a 25 ft contour interval, exist on the anticline with the largest centered in SW Sec 20-T153N-R101W. Minimum closure on this structure is 26 ft. Other mapped closures exist in SE Sec 32-T153N-R101W, in SE 6-T152N-R101W, and in NE Sec 9-T152N-R101W. Structural relief decreases to the southeast (basinward) down the plunge of the anticline. This structure is also slightly asymmetric, the northeast flank being steeper than the southwest flank.

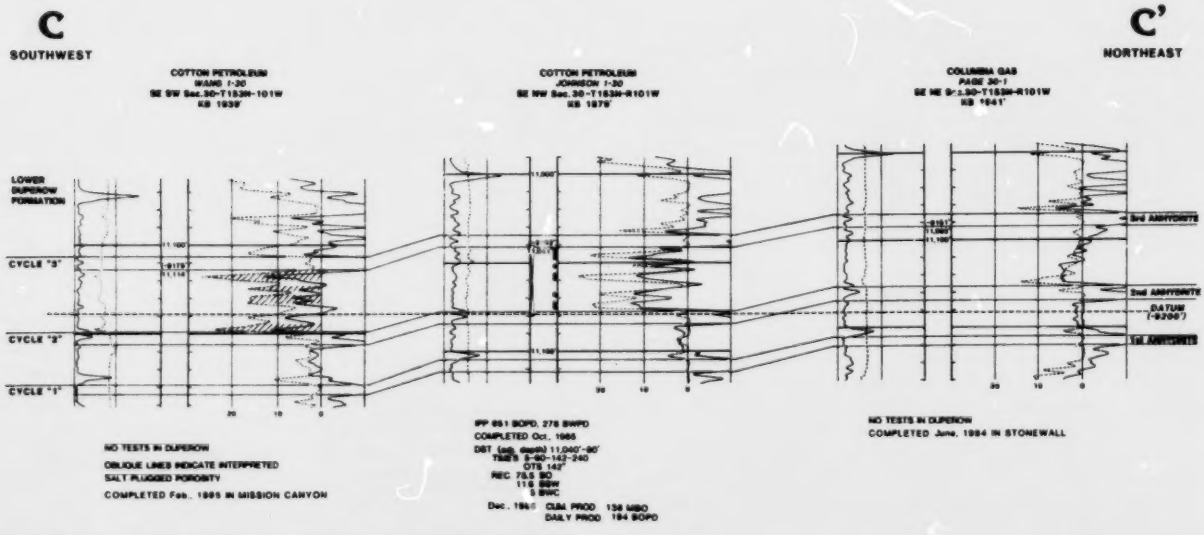


Fig. 11 Devonian Duperow Formation structural cross-section, FDC-CNL logs. Refer to Fig. 12 for line of section.

Table 3. Duperow production data, Indian Hill Field area.

Well Name Location	Gross Porosity Thickness (1)	Initial Potential BOPD Date	Cum. Prod. MBO (Dec 1986)	Current Prod. BOPD (Dec 1986)
Pedersen 5-24-4A SE SW 24-153-102	5	477 June 1985	152	187
Johnson 1-30 SE NW 30-153-101	15	651 Oct 1985	136	194
Nelson 2-2 SW SE 1-152-102	14	325 June 1984	107	81
Erickson 4-25 NE NE 25-153-102	9 (2)	488 Oct 1985	88	166
Papineau 1-17-4C SE SE 17-153-101	5	323 Jan 1985	87	57
Eckart Found. 5-12-B NW NW 5-152-101	2	98 Oct 1984	38	42
Fjelstad 3-6 SW NW 6-152-101	12	207 May 1986	28	90
C.W. Patch Fed #1 SE SE 14-153-102	6	82 July 1985	18	67
Habermeyer 33-13 NW SE 13-153-102	0 (3)	103 Dec 1985	17	recomp
Metzger 1-19 SW SW 19-153-101	2	170 Sept 1985	10	recomp
State 2-19 SE SE 19-153-101	6	206 Dec 1986	2	206

(1) Total thickness in feet of porosity in zone (3rd cycle) greater than 10% FDC-CNL log. Rugose hole may affect accuracy of logs.
(2) Also perforated in additional Duperow zones.
(3) Maximum porosity is approximately 9.5%.

The Mission Canyon structure is larger, broader, and has less closure than the deeper structures. It is also better defined due to greater well control at this shallower objective. The difference between the highest producing well (the Columbia Gas Deer Pass 20-3 in SE SW 20-T153N-R101W: - 7195') and the lowest producing well (the Superior 14-1 Lindvig-Davidson A in SW NW 14-T152N-R101W: - 7349') is 154 ft. No apparent oil-water contact for the Mission Canyon reservoir has been found in the Indian Hill Field area. All the wells have some water production but the percentage is not related to structural position.

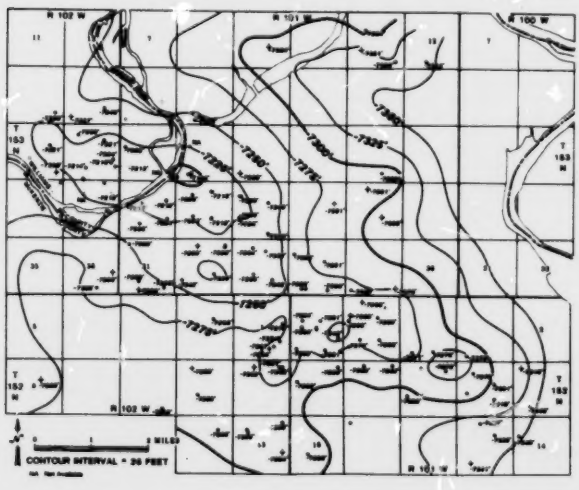


Fig. 13 Mississippian Mission Canyon Formation structure map.

STRATIGRAPHY

In the late 1970s, several significant Mission Canyon fields were discovered in the central portion of the Williston Basin, including Mondak, Little Knife, and the Billings Nose complex. The Mission Canyon reservoir at Mondak has been described as a tight (2-4 per cent porosity), fractured, fossiliferous limestone (Byrd, 1978; and Parker and Hess, 1980). The limestone was probably deposited under open-marine conditions. The reservoir facies at both Little Knife and the Billings Nose complex were deposited in shallow subtidal shoaling to peritidal conditions in a regressive, shallowing-upward sequence (Wittstrom and Hagemeier, 1978; Altschuld and Kerr, 1982; Lindsay and Roth, 1982; and Lindsay and Kendall, 1985). Significant porosity, up to 30 per cent, exists in these regressive sequence reservoirs, much of it secondary due to dolomitization.

In the Indian Hill Field area, the Mission Canyon produces from a moderate porosity zone (2-16 per cent FDC-CNL) at or near the top of the Mission Canyon (Fig. 14). This zone is referred to as the "Nesson" or "Rival" zone by some operators in the area but will be referred to as the upper Mission Canyon zone in this report.

Unlike the reservoirs of Little Knife and the Billings Nose, the Indian Hill reservoir consists of primary porosity which was formed during deposition by a transgressive sequence. Core descriptions from Columbia Gas Deer Pass 20-1 (SW SW 20-T153N-R101W), Rehab 28-1 (SW NW 28-T153N-R101W), Page 30-1 (SE NE 30-T153N-R101W), and the Cotton Fredrickson 1-2 (SW NE 2-T152N-R102W) all indicate a common transgressive sequence of deposition in progressively deeper water. There are 3 distinct facies: a lower restricted marine mudstone, a middle higher energy packstone-grainstone to boundstone, and an upper open marine skeletal wackestone to packstone.

The lower restricted marine mudstone is interbedded with peloidal packstone and wackestone which would indicate close proximity to the shoaling facies. It has low faunal diversity and is locally bioturbated.

The middle facies which contains the porosity consists of two sub-facies: a peloidal-oncoidal packstone to grainstone and an algal boundstone. The porosity in the Fredrickson 1-2, located well off-structure (SW NE 2-T152N-R102W), is dominated by a blue-green algal buildup, whereas the porosity of the Deer Pass 20-1 (SW SW 20-T153N-R101W) and the Rehab 28-1 (SW NW 28-T153N-R101W), both located at or near the crest of the structure, are dominated by the oncoidal-peloidal packstone to grainstone. The packstone-grainstone facies would have been deposited in a shoaling environment with higher energy conditions. The porosity in the Page 30-1, located in an intermediate structural position (SE NE 30-T153N-R101W), consists of an oncoidal-peloidal packstone with an important algal constituent, indicative of alternating lower and higher energy. The increased abundance of both the micrite of the packstone and the algae would indicate generally lower energy conditions. Log characteristics are not distinctly different between the porosity types (Fig. 14).

Based on this limited core data, an interpretation regarding paleostructure, energy setting, and the porous middle facies may be made assuming the present-day structure is similar to the paleostructure (Fig. 15). The areas near the higher portions of the structure should be dominated by the peloidal-oncoidal packstone to grainstone shoal and the areas on the perimeter of the shoal should be dominated by the lower energy algal

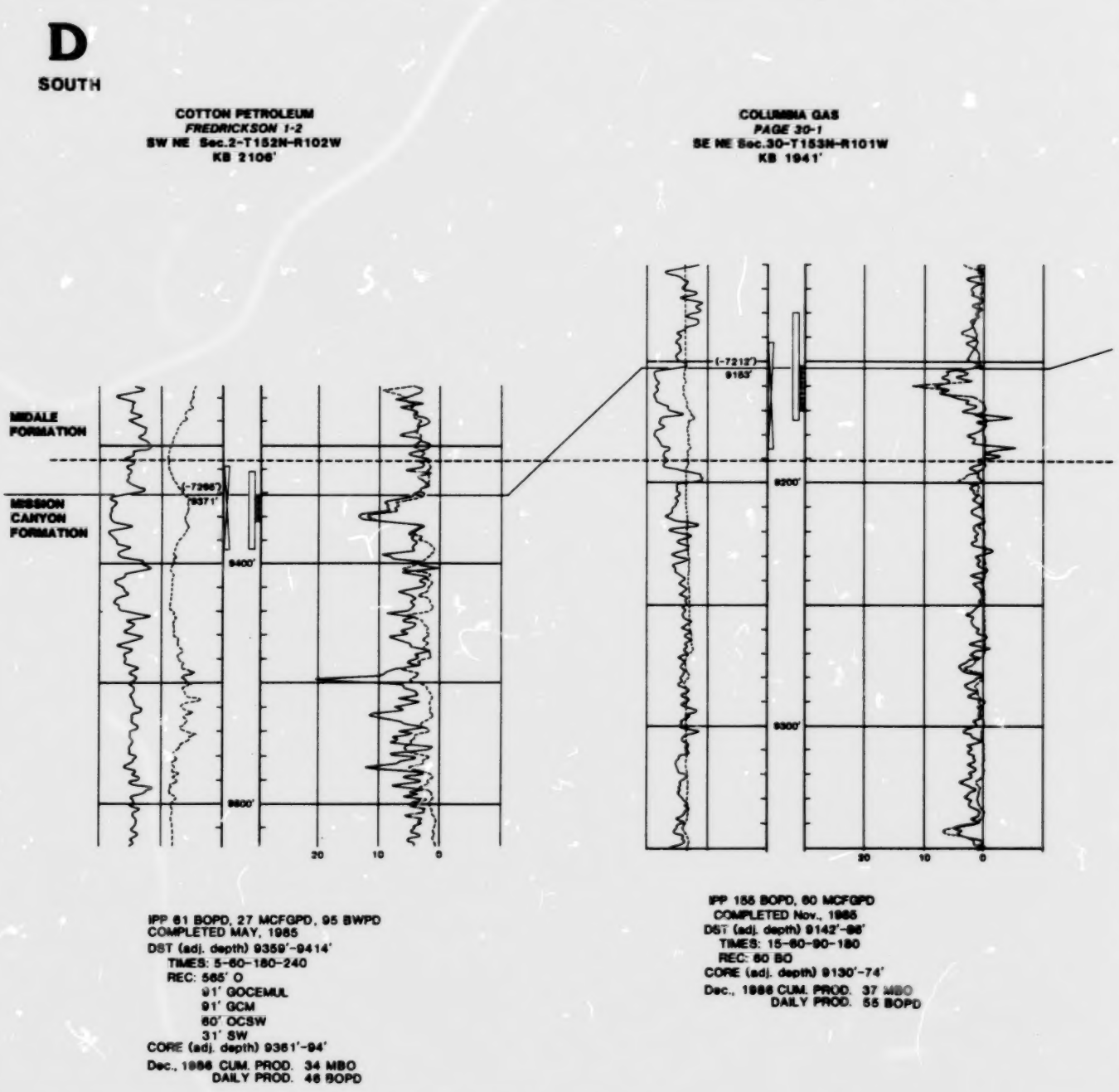


Fig. 14 Mississippian Mission Canyon structural cross-section, FDC-CNL logs. Refer to Fig. 16 for line of section.

buildups. Deposition in the intermediate areas would have both the packstone-grainstone and boundstone facies. This may be an important factor regarding the productivity of the wells in the field area and will be addressed in the next section of this report.

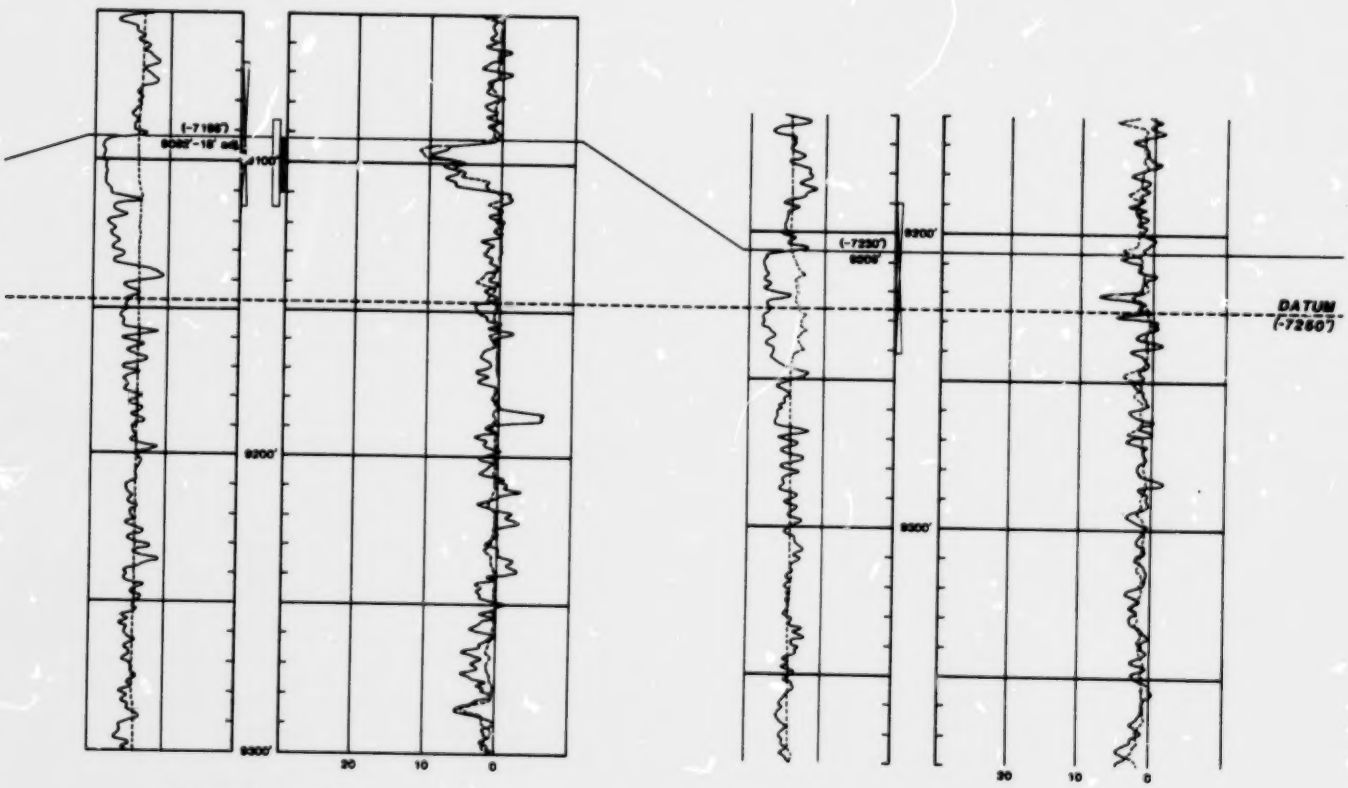
A reduction in primary porosity by calcite and dolomite cement and some bituminous material is evident in the core data. There is no significant dolomitization of the reservoir facies.

The uppermost facies is a non-porous, argillaceous skeletal wackestone to packstone which is actually the lower part of the Midale Formation (Fig. 14). It is locally laminated, bioturbated, and highly fossilferous with a high faunal diversity. This is interpreted to represent deposition in a shallow open-marine setting.

D'
NORTH

COLUMBIA GAS
DEER PASS 20-1
SW SW Sec.20-T153N-R101W
KB 1879'

COLUMBIA GAS
REHAB 21-1
SW SW Sec.21-T153N-101W
KB 1976'



IPF 504 BOPD, 262 MCFGPD
COMPLETED July, 1985 IN
DEER PASS 20-3 (twin well)
EQUIVALENT PERFED ZONE IS INDICATED ON
DEER PASS 20-1
DST (adj. depth) 9067'-9115'
TIMES: 15-60-90-150
REC: 96 BO
CORE 9066'-9115'
Dec., 1986 CUM. PROD. 191 MBO
DAILY PROD. 385 BOPD

TEMP. ABN.
DST 9190'-9241'
TIMES: 15-45-15'-360
REC: 171'M

RESERVOIR DEVELOPMENT AND PRODUCTION DATA

The Mission Canyon is the most widespread and developed productive interval in the Indian Hill Field area, with 60 wells (plus 1 shut-in and 1 recompleted). The porosity is generally coincident with the Mission Canyon structure and extends the entire length of the field area (Figs. 13, 16). Porosity is generally greater and thicker along the axis of the structure with a definite decrease toward the margins. Localized facies variations may account for the differences of the porosity and productivity of the reservoir.

Cumulative production (December 1986) indicates a general correlation with the areas of best production and the shoaling facies along the axis of the structure (Figs. 15, 17). Assuming that the higher parts of the structure are most likely in the shoaling packstone-grainstone facies, the original stratigraphy is an integral factor in the productivity of the Mission Canyon. Some of the structurally lower wells which are better than other adjacent producers, most notably the Cotton Wang 1-31 (SE SE 31-T153N-R101W), may be explained as follows:

1) the area was on a paleohigh "shoaling" area but is on the flank of the present-day structure,

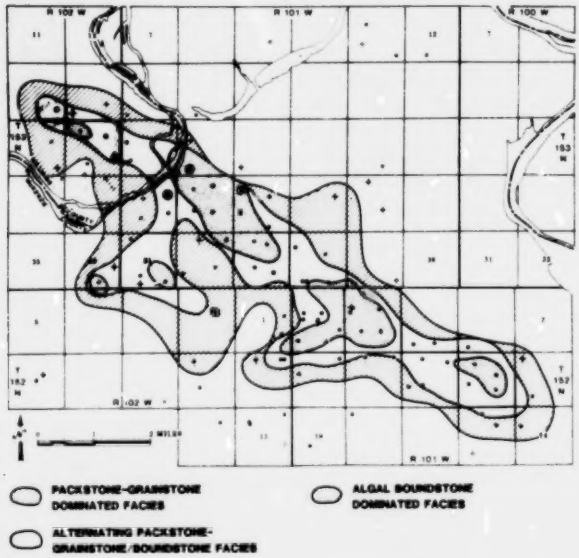


Fig. 15 Interpretive facies map of Upper Mission Canyon porous interval. This interpretation is based on the 4 cored wells indicated by enclosing circles. Note correlation to production in Figures 17 and 18.

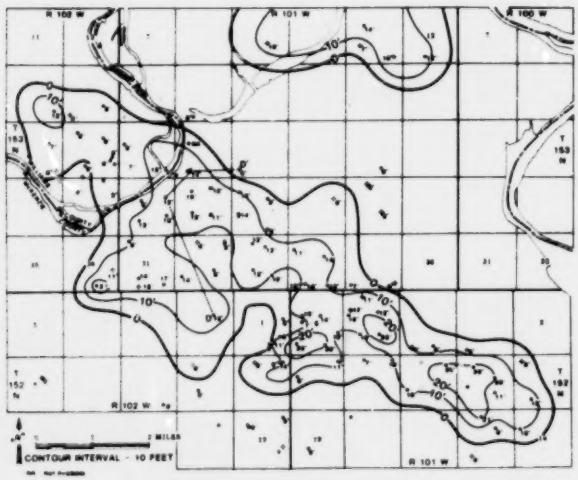


Fig. 16 Mississippian Mission Canyon Formation porosity isopach map. Porosity cut-off is greater than 3 per cent on FDC-CNL logs (rugose hole may affect accuracy of logs). Location of Mission Canyon cross-section is indicated by the dashed line D-D'.

2) the packstone-grainstone sediment was transported off structure by currents or storms, or
3) exceptional porosity and permeability developed in the algal buildup facies.

Some oolitic material was noted in the cuttings from the Wang 1-31 making one of the first two explanations more likely. The other structurally lower wells (which are poorer producers) are assumed to have been deposited in a lower energy setting with a greater dominance of the algal boundstone facies.

The current daily production (as of December 1986) also correlates to the structurally higher areas in the interpreted packstone-grainstone facies (Fig. 18). Reservoir pressure has declined from 4650 psi in 1983 to approximately 2200 psi in late 1985. This drop has had a negative effect on the productivity of wells which were completed later in the history of field development.

Core data indicated mostly sparse natural fractures. Some of the wells in the field area were fracture stimulated with generally good success; production increases of up to two to three times were achieved.

Cumulative production from the Mission Canyon reservoir is approximately 4,833 MBO; daily production is 3292 BOPD, as of December 1986.

SUMMARY

The Indian Hill Field area (which includes Hardscrabble Field and a portion of Camp Field) is on an anomalously large structure with multiple pay zones. Original production was established in 1978 from the Red River, the deepest productive formation in the area. Subsequent drilling and recompletions in the 1980s have proven 5 more producing formations over a productive area approximately 10 miles long and up to 3.5 miles wide. The primary producing formations are the Ordovician Red River,the Silurian Stonewall, the Devonian Duperow, and the Mississippian Mission Canyon. The Devonian Nisku and Mississippian Ratcliffe Formations are also productive on a limited basis.

The overall structure is a slightly asymmetric (steeper to the north) southeast plunging anticline with several areas of closure with dimensions of 0.5 to 4.2 miles. The structure, which persisted throughout Phanerozoic time, is probably basement controlled and had an effect on the depositional environments and reservoir development of the productive intervals.

The stratigraphy and porosity development can be complex with rapid lateral variations. Porosity can form on the tops or the flanks of the structures. The density of drilling in the Indian Hill Field area offers insight into how these stratigraphic and structural changes control productivity. The following generalizations may be made concerning the 4 main productive formations:

1) The best Red River production is from the "D" zone which occurs on the flanks of the structures. The "B" and "C" zones produce from the tops of the structures.
2) The Stonewall production is the best production in the field (on a per well basis), and occurs in relatively limited areas where favorable porosity fairways intercept structurally high portions of the field.
3) The Duperow produces from several areas downdip from the crest of the structure in a porosity fairway which partially encircles the structure. Duperow porosity shows rapid lateral variations; production is best in wells which are near the center of the porosity fairways.
4) The Mission Canyon production is the most widespread and is best where a packstone-grainstone facies porosity development is coincident with the highest areas of the plunging anticline.

The porosity of the Mission Canyon is primary, formed in a transgressive sequence, whereas the porosity of the Duperow, Stonewall, and Red River is due to secondary dolomitization. Adverse stratigraphic effects include small crystal size, poorly

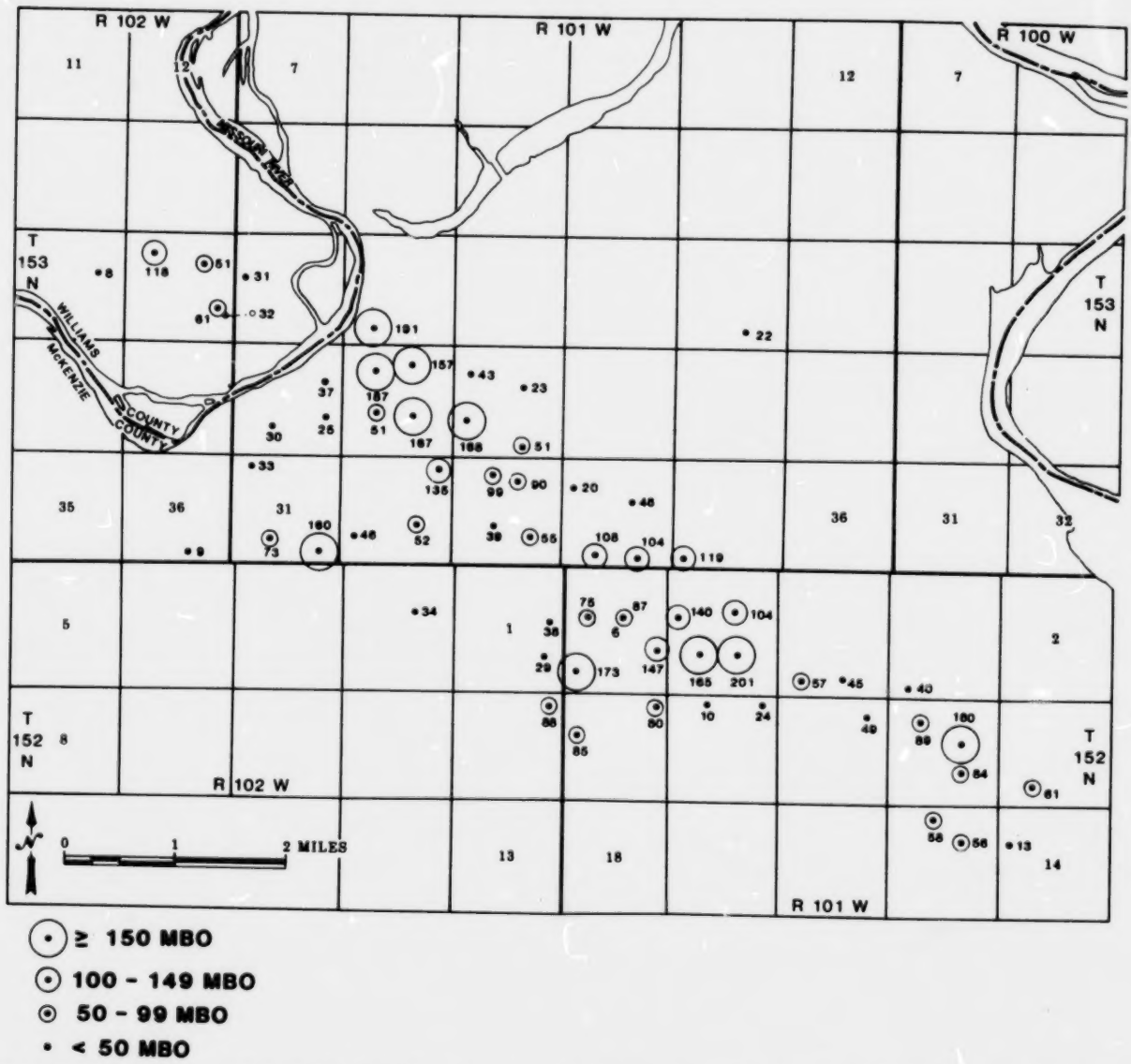


Fig. 17 Cumulative Mission Canyon production through December 1986. Numbers adjacent to symbols indicate cumulative oil production through December 1986. All non-Mission Canyon producing wells have been removed as well as wells outside the Hardscrabble - Indian Hill - Camp study area.

connected pore throats, bitumen plugging and salt plugging, all of which can limit the extent and productivity of the reservoirs.

Regional and detailed local geologic studies involving paleoenvironmental reconstructions must be made in order to try to understand and predict the occurrence of hydrocarbon reservoirs.

Like many of the multiple-pay fields in the Williston Basin, it is the occurrence of "stacked" pays that makes the economics of exploration and development attractive in the Indian Hill Field area. Multiple-pay potential exists in a large portion of the Williston Basin and in order to improve success and economics in an exploration or development program, the geologic analysis must be thorough and reviewed carefully and without bias to realize the full productive potential of the basin.

ACKNOWLEDGEMENTS

The author thanks Matt Mannick, Dave Pitzl, and Steve Williams for their reviews and suggestions; and the rest of the Cotton Petroleum Corporation organization which was involved in the Indian Hill Field. Special thanks go to Marianne Dobler for the manuscript preparation and to Kirk Hicks for drafting the figures. John Santos of Columbia Gas is also thanked for providing information.

The author is grateful to Apache Corporation for its support and permission to present this paper.

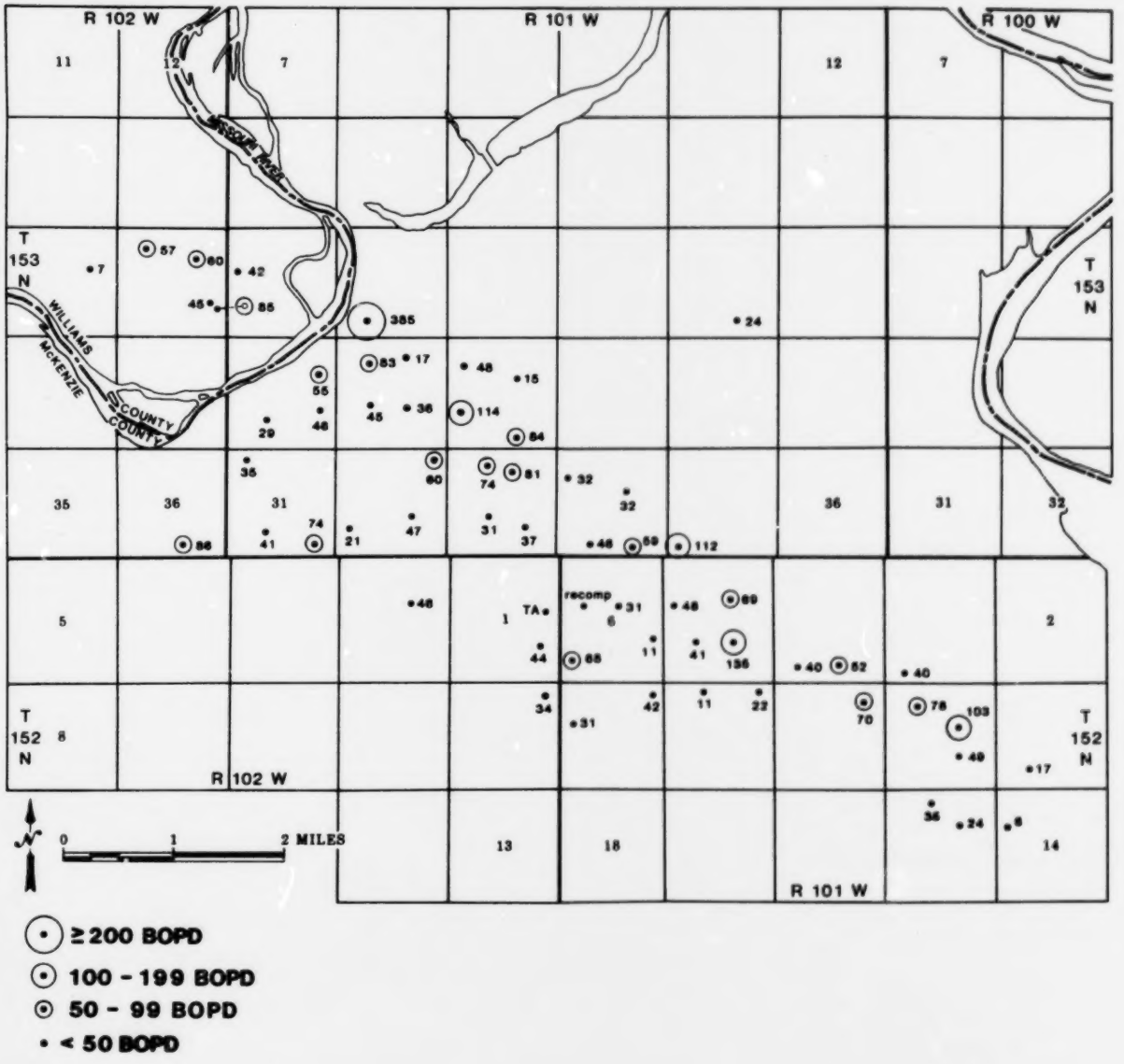


Fig. 18 Mission Canyon production BOPD, December 1986. Numbers adjacent to symbols indicate average daily oil production in December 1986. All non-Mission Canyon producing wells have been removed as well as all wells outside the Hardscrabble - Indian Hill - Camp study area.

REFERENCES CITED

Altschuld, N., and S. D. Kerr, Jr., 1982, Mission Canyon and Duperow reservoirs of the Billings nose, Billings County, North Dakota: Saskatchewan Geological Society and North Dakota Geological Society Special Publication No. 6, Fourth International Williston Basin Symposium, p. 103-112.

Asquith, G. B., R. L. Parker, C. R. Gibson, and J. R. Root, 1978, Depositional history of the Ordovician Red River C and D zone, Big Muddy Creek field, Roosevelt County, Montana: Montana Geological Society Guidebook, 1978 Williston Basin Symposium, p. 71-76.

Ballard, W. W., 1969, Red River of northeast Montana and northwest North Dakota: Montana Geological Society Guidebook, Eastern Montana Symposium, p. 15-24.

Bluemle, J. P., S. B. Anderson, and C. G. Carlson, 1980, North Dakota stratigraphic column: North Dakota Geological Survey.

Burke, R. B., and G. L. Stefanovsky, 1982, Porosity types, geometry and interpore minerals of the lower Duperow Formation, Billings Nose area, Williston Basin: Saskatchewan Geological Society and North Dakota Geological Society Special Publication No. 6, Fourth International Williston Basin Symposium, p. 93-100.

Byrd, W. J., 1978, Geology of the Mondak West and Mondak fields in Richland County, Montana, and McKenzie County, North Dakota: Montana Geological Society Guidebook, 1978 Williston Basin Symposium, p. 307-311.

Carlson, C.G., and S. B. Anderson, 1966, Sedimentary and tectonic history of North Dakota part of Williston Basin: AAPG Bulletin, v. 49, p. 1833-1846.

Carroll, W. K., 1979, Depositional environments and paragenetic porosity controls, upper Red River Formation, North Dakota: North Dakota Geological Survey Rept. Inv. 66, 51 p.

Clement, J. H., 1985, Depositional sequences and characteristics of Ordovician Red River reservoirs, Pennel field, Williston Basin, Montana: Carbonate Petroleum Reservoirs, Springer-Verlag, New York, p. 72-84.

Davies, G.R., 1979, Dolomite reservoir rocks: proceses, controls, porosity development: Geology of Carbonate Porosity, AAPG Ed. Course Note Series #11, p. C1-17.

Derby, J. R., and J. T. Kilpatrick, 1985, Ordovician Red River dolomite reservoirs, Killdeer field, North Dakota: Carbonate Petroleum Reservoirs, Springer-Valley, New York, p. 60-69.

Dunham, J. B., and E. R. Olson, 1978, Diagenetic dolomite formation related to Paleozoic paleogeography of the Cordilleran miogeocline in Nevada: Geology, v. 6, p. 556-559.

Gerhard, L. C., S. B. Anderson, J. A. LeFever, and C. G. Carlson, 1982, Geological development, origin, and energy mineral resources of Williston Basin, North Dakota: AAPG Bulletin, v. 66, p. 989-1020.

Hoganson, J. W., 1978, Microfacies analysis and depositional environments of the Duperow Formation (Frasnian) in the North Dakota part of the Williston Basin: Montana Geological Society Guidebook, 1978 Williston Basin Symposium, p. 131-144.

Irwin, M. L., 1965, General theory of epeiric clear water sedimentation: AAPG Bulletin, v. 49, p. 445-459.

Kendall, A. C., 1976, The Ordovician carbonate succession (Big Horn Group) of southeastern Saskatchewan: Department of Mineral Resources, Saskatchewan Geological Survey Report 180, 185 p.

—— 1984, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: discussion: AAPG Bulletin, v. 68, p. 776-779.

Kohm, J. A., and R. O. Louden, 1978, Ordovician Red River of eastern Montana-western North Dakota; relationships between lithofacies and production: Montana Geological Society Guidebook, 1978 Williston Basin Symposium, p. 99-117.

Lindsay, R. F., and M. S. Roth, 1982, Carbonate and evaporite facies, dolomitization and reservoir distribution of the Mission Canyon Formation, Little Knife field, North Dakota: Saskatchewan Geological Society and North Dakota Geological Society Special Publication No. 6, Fourth International Williston Basin Symposium, p. 153-179.

—— and C. G. St. C. Kendall, 1985, Depositional facies, diagenesis, and reservoir character of Mississippian carbonates in the Mission Canyon Formation, Little Knife field, Williston Basin, North Dakota: Carbonate Petroleum Reservoirs, Springer-Verlag, New York, p. 176-190.

Longman, M. W., T. G. Fertal, and J. S. Glennie, 1983, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: AAPG Bulletin, v. 67, p. 744-771.

—— 1984, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: reply: AAPG Bulletin, v. 68, p. 780-784.

Murray, G. H., 1968, Quantitative fracture study — Sanish pool, McKenzie County, North Dakota: AAPG Bulletin, v. 52, p. 117-125.

Parker, J. M., and P. D. Hess, 1980, The Mondak Mississippian oil field, Williston Basin, U.S.A.: Oil and Gas Journal, Oct. 13, 1980, p. 210-217.

Parker, T. S., and W. H. Powe, 1982, Geology of the Raymond field area, Sheridan County, Montana: Saskatchewan Geological Society and North Dakota Geological Society Special Publication No. 6, Fourth International Williston Basin Symposium, p. 225-234.

Pilatzke, R. H., D.W. Fischer, and C. L. Pilatzke, 1985, Stratigraphic controls on Duperow production in Williston Basin, Montana and North Dakota (abs.): AAPG Bulletin, v. 69, p. 680.

Porter, J. W., and J. G. C. M. Fuller, 1959, Lower Paleozoic rocks of northern Williston Basin and adjacent areas: AAPG Bulletin, v. 43, p. 124-189.

Roehl, P., 1967, Carbonate facies, Williston Basin and Bahamas: AAPG Bulletin, v. 51, p. 1979-2032.

Ruzyla, K., and G. M. Friedman, 1985, Factors controlling porosity in dolomite reservoirs of the Ordovician Red River Formation, Cabin Creek field, Montana: Carbonate Petroleum Reservoirs, Springer-Verlag, New York, p. 40-58.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society America Bulletin, v. 74, p. 93-114.

Walsh, M. H., 1969, Fairview area, Richland County, Montana: Montana Geological Society Guidebook, Eastern Montana Symposium, p. 129-134.

Wilson, J. L., 1967, Carbonate-evaporite cycles in lower Duperow Formation of Williston Basin: Canadian Petroleum Geologists, v. 15, p. 230-312.

—— 1975, Carbonate Facies in Geologic History: Springer-Verlag, New York, p. 471.

Wittstrom, M. D., and P. C. Chimney, 1980, Proposed model for development of Red River (Ordovician) porosity, eastern Montana and western North Dakota (abs.): AAPG Bulletin, v. 64, p. 804-805.

—— and M. E. Hagemeier, 1978, A review of Little Knife field development, North Dakota: Montana Geological Society Guidebook, 1978 Williston Basin Symposium, p. 361-368.

USING CAPILLARY PRESSURE TECHNIQUES TO MAP AND IDENTIFY AN ECONOMIC FAIRWAY IN THE ORDOVICIAN RED RIVER ON THE WESTERN FLANK OF THE WILLISTON BASIN

JEFFREY B. JENNINGS

Consulting Geologist
2156 South Field Street
Lakewood, Colorado

ABSTRACT

Capillary pressure curves have been confined mainly to the realm of petroleum engineering but have some excellent applications in petroleum geology. Capillary pressure, for any rock type possessing porosity and permeability, can be viewed as the force required to push a fluid through a given pore size. The raw data are collected by injecting mercury, at increasing pressures, into plugs obtained from core or side wall samples. These measurements, when plotted, produce a curve of injection pressure versus fluid saturation from which a number of parameters can be extracted for the purposes of interpretation and mapping. Pore throat sorting, reservoir grade and oil columns required for economic oil saturations are some of the more important of these parameters.

Pore throat sorting is an empirical number which reflects the pore geometry. It is highly influenced by the diagenetic history and grain- or crystal-sorting, thus making it useful as a stratigraphic indicator.

Reservoir grade is a number which defines the rock's ability to accept fluid and permits qualitative comparisons between reservoirs.

Oil column heights can be calculated to define the vertical trap closure (structural or stratigraphic) required to achieve economic oil accumulations. A 50 per cent oil saturation approximates the conditions for which marginal production can be expected while a 75 per cent oil saturation should result in good economic oil production.

Pore throat sorting, reservoir grade and oil column heights may be compiled and contoured to produce exploratory maps. The maps are useful for delineating "Oil Reservoir Fairway" trends and highlighting areas in which to concentrate further investigative efforts.

A capillary pressure study was conducted on the third porosity of the Ordovician Red River Formation on the western flank of the Williston Basin in Montana and North Dakota. Sixteen wells with core data were sampled and mercury injection capillary pressures were obtained. Values for pore throat sorting, reservoir grade and oil column requirements for 50 per cent and 75 per cent oil saturation were then plotted and contoured to produce four regional maps. Each of the four maps identified a north-south trending fairway along the Montana-North Dakota border containing the best development of reservoir rock. The maps provide a good example of how capillary pressure techniques can be applied to assist with exploration programs.

OBTAINING AND DISPLAYING CAPILLARY PRESSURE DATA

Capillary pressure data are obtained by injecting mercury, at increasing pressure levels, into sample plugs. The plugs, normally the same plugs used in routine core analysis, are approximately one inch in diameter and 1.5 inches in length. After a plug is thoroughly cleaned, its porosity is measured and it is placed within the sample chamber of the capillary pressure apparatus (Fig. 1). A strong vacuum is applied to reduce the pressure down toward zero atmosphere and the chamber is filled with mercury up to an index mark located in an observation port immediately above the chamber. A micrometer handwheel, controlling the mercury reservoir, is set to zero and pressure is then applied to the system. Measurements at thirty pressure levels are normally obtained starting at 2 psi and progressing, in a logarithmic fashion, up to 2000 psi. At each pressure level the system is allowed to reach equilibrium as the sample plug imbibes mercury. When the mercury will no longer saturate the sample at a given pressure, the mercury level is re-indexed by turning the micrometer handwheel to force more mercury into the chamber. The quantity of mercury needed to replenish the sample chamber equals the amount imbibed into the plug and can be read directly from the micrometer. By dividing this measurement by the total pore volume of the plug, a calculation of injection pressure (psi) versus mercury saturation (per cent pore space) can be made.

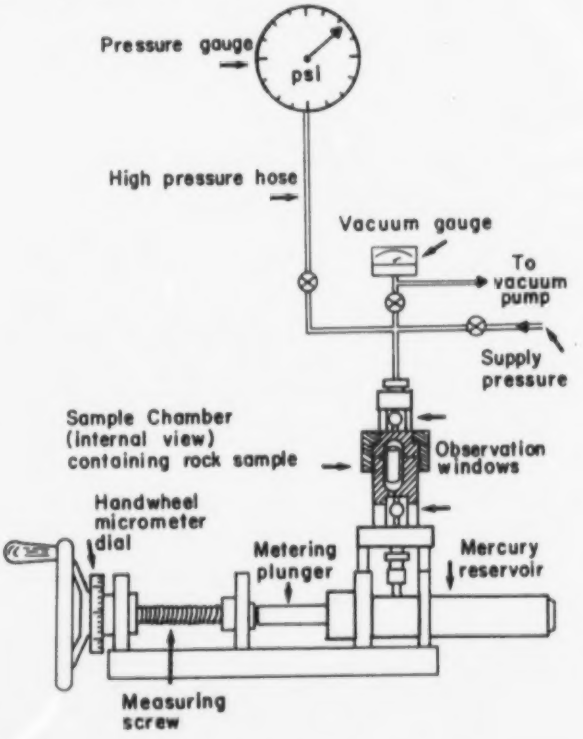


Fig. 1 Capillary pressure apparatus for obtaining mercury injection capillary pressure data.

To make the task of interpretation easier, the tabulated data of injection pressure versus mercury saturation are plotted on a semi-log graph (Fig. 2). Mercury saturation is plotted along the bottom scale and ranges linearly from 0 to 100 per cent while the injection pressure is plotted on the vertical scale and ranges logarithmically from 2 to 2000 psi. Plotted along the top is another horizontal scale measuring irreducible pore space and is simply the reciprocal of the mercury saturation scale. An additional vertical scale of pore throat radius, in microns, is usually displayed next to injection pressure and provides an estimate of the size of the pore throats at a given pressure. Capillary pressure data may also be plotted using a linear format but, for accuracy and interpretation considerations, the semi-log format is preferred. Subtle differences between curves normally occur at injection pressures below 200 psi and these differences become much more apparent on a semi-log plot than on a linear plot.

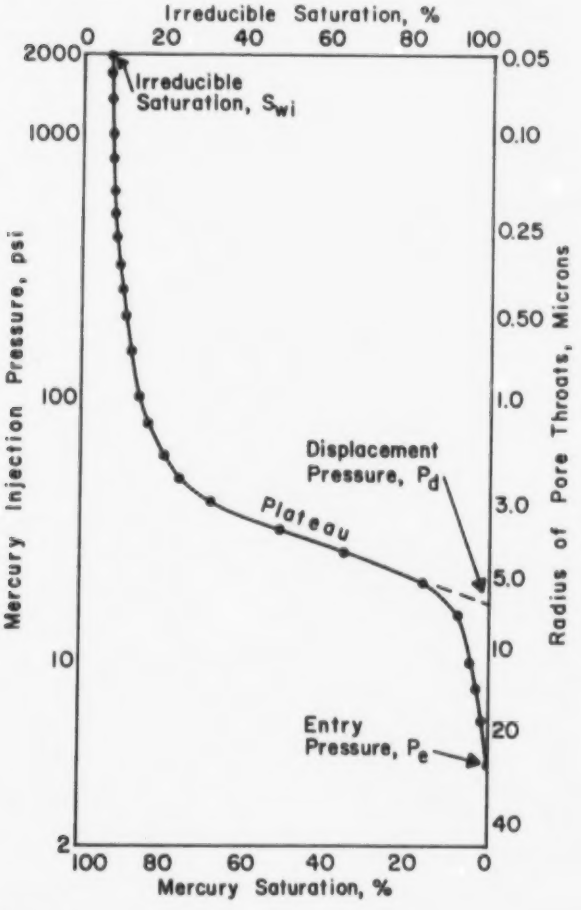


Fig. 2 A typical capillary pressure curve plotted on a semi-log graph.

Each capillary pressure curve can be uniquely defined by the entry pressure, displacement pressure, plateau and irreducible saturation (Fig. 2). The entry pressure, P_e, is the pressure at which the sample first begins to accept mercury into the pore system. It is of limited importance and is primarily a function of the mercury conforming to irregularities on the surface of the sample plug. Displacement pressure, P_d, is estimated by extending the slope of the plateau out to the right side of the graph. It is interpreted to be the pressure at which mercury first begins to imbibe into the rock at reservoir conditons. The plateau is reflective of the sorting of the pore throats within a sample. A horizontal plateau indicates good sorting with sorting becoming poorer as the plateau increases in steepness. Irreducible saturation, S_{wi}, is that percentage of pore space which mercury cannot enter. It may be used to adjust the laboratory-measured total porosity to the true effective porsity.

PARAMETERS INTERPRETED FROM CAPILLARY PRESSURE DATA

A number of parameters can be extracted from capillary pressure data for mapping and evaluation purposes. A few of these are pore throat sorting, reservoir grade and oil columns for 50 per cent and 75 per cent oil saturations. Figure 3 provides a comparison of these four parameters in relationship to a number of capillary pressure curves.

20%	20%	20%
0.5md	10md	350md
PORE THROAT SORTING		
1.2	4.2	1.2
RESERVOIR GRADE		
28	21	5
OIL COLUMN 50% SATURATION		
170'	60'	6'
OIL COLUMN 75% SATURATION		
210'	130'	8'

Fig. 3 Three capillary pressure curves and their respective values for Pore Throat Sorting, Reservoir Grade, Oil Column for 50 per cent saturation and Oil Column for 75 per cent saturation.

PORE THROAT SORTING (PTS), as the name implies, is a number which measures the sorting of the pore throats within a rock sample. It ranges from 1.0 (perfect sorting) upwards to 8.0 (essentially no sorting) with most rock samples falling between 1.2 and 5.0. PTS indicates the slope of the plateau formed by the capillary pressure curves and is calculated with the following equation:

$$PTS = \left[\frac{\text{Third Quartile Pressure}}{\text{First Quartile Pressure}}\right]^{1/2}$$

Where the first and third quartile pressures are obtained directly from the capillary pressure curve and reflect the 25 per

cent and 75 per cent mercury saturation pressures adjusted for irreducible saturation. A PTS value of 1.0 would repesent a perfectly horizontal plateau while values much above 5.0 pertain to curves displaying little or no plateau development. The significance of PTS centers around the rock's ability to accept oil saturation. In well sorted rocks, once a threshold buoyancy pressure is obtained, oil will rapidly saturate the available porosity up to the maximum capacity. Poorly sorted rocks require a pressure increase over a much broader range to obtain the same level of oil saturation. Because lithology greatly influences the pore geometry, pore throat sorting can be viewed as a stratigraphic indicator. Figure 4 presents an example of how pore throat sorting is calculated from a capillary pressure curve.

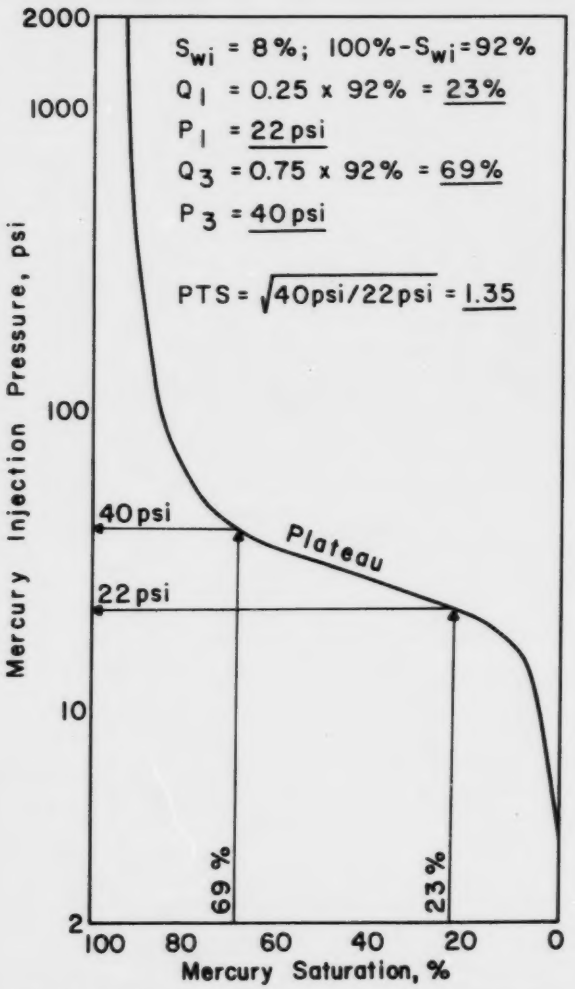


Fig. 4 Calculating Pore Throat Sorting (PTS) using injection pressure values from the first and third quartile of the capillary pressure curve.

RESERVOIR GRADE (RG) is an indicator of the reservoir quality of a rock and ranges from zero (best quality) to 100 (lowest quality). It is simply the percentage of linear area integrated under the capillary pressure curve and can be calculated by making a linear plot of the data on graph paper and counting the squares. While PTS measures the range in pore throat sizes, RG provides a relative number to the size of the pore throats. A low RG number indicates large pore throats and the ability to accept oil saturation at low buoyancy pressures. The larger the RG number becomes, the smaller the pore throats and the greater the buoyancy pressure needed to obtain economic oil saturations. Reservoir grade, in conjunction with pore throat sorting, can provide a good evaluation of a reservoir.

Oil columns can be calculated for any oil saturation but, for comparison and mapping purposes, are fixed at 50 per cent and 75 per cent. The numbers are not arbitrary in that a 50 per cent oil saturation will commonly yield a marginal to fair well while oil saturations of 75 per cent or greater can be expected to yield good to excellent wells. In practice, the oil column values can be used to determine the minimum trap relief, either structural or stratigraphic, needed to obtain a 50 per cent or 75 per cent oil saturation at the top of the trap. In exploration programs, this type of data can be used to high-grade prospects. For field development, oil column data are useful for locating offset drilling which will remain within the productive economic limits of the oil column.

Calculating an oil column consists of first determining the density gradients (psi/ft) of the oil and formation water. The difference in the density gradients defines a buoyancy force which constitutes the driving mechanism for oil to migrate into the reservoir rock. The second element needed is the injection pressure from a capillary pressure curve at a given mercury saturation (i.e. oil saturation). Calculating the oil column is then a process of converting the injection pressure value from a mercury-air system to an oil-water system and dividing this number by the previously calculated buoyancy force. The resulting number represents the feet of vertical oil column needed to achieve the oil saturation. For a more detailed discussion on calculating oil columns, the reader is directed to papers by Purcell (1949), Smith (1966) and Schowalter (1979).

MAPPING CAPILLARY PRESSURE DATA

Capillary pressure data have in the past been used primarily for development purposes to evaluate reservoir rock quality, calculate oil-water contacts or estimate relative permeability characteristics. Stout (1964) presented the concept of using capillary pressure data as a tool to evaluate petrophysical characteristics. His concept makes it possible for capillary pressure data to be applied on a regional basis in much the same fashion as more conventional stratigraphic studies. Regional maps based on pore throat sorting, reservoir grade and oil columns required for 50 per cent and 75 per cent oil saturations can be generated to identify areas with the best reservoir rock or to determine the minimum economic trapping requirements. Other values such as effective porosity or displacement oil columns may also be mapped. It should be emphasized that capillary pressure studies are not substitutes for stratigraphic studies but are complementary to them. Where stratigraphic studies identify facies and depositional environments, capillary pressure studies measure the quality of these facies as reservoirs.

A capillary pressure study was conducted on the third porosity of the Ordovician Red River Formation in the Williston Basin of Montana and North Dakota. Sixteen wells with core data were sampled and mercury injection capillary pressures were selected from the very best effective foot of reservoir rock in each core. Values for pore throat sorting, reservoir grade and oil column requirements to obtain 50 per cent and 75 per cent oil saturations were then plotted and contoured to produce four regional maps (Figs. 5 to 8). While some might view this as presenting an overly optimistic picture, it should be remembered that the maps are regional and designed to be guides for exploration. The four maps

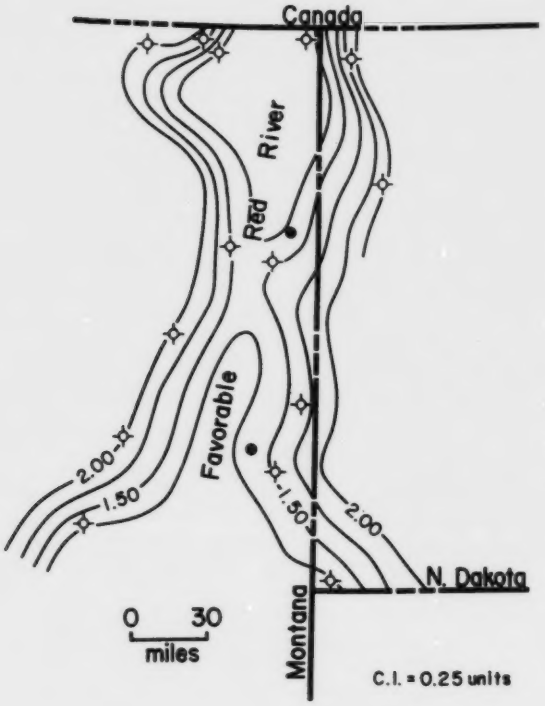


Fig. 5 Contour map of Pore Throat Sorting from the third porosity of the Ordovician Red River. A fairway of favorable reservoir rock lies inside the 1.50 units contour.

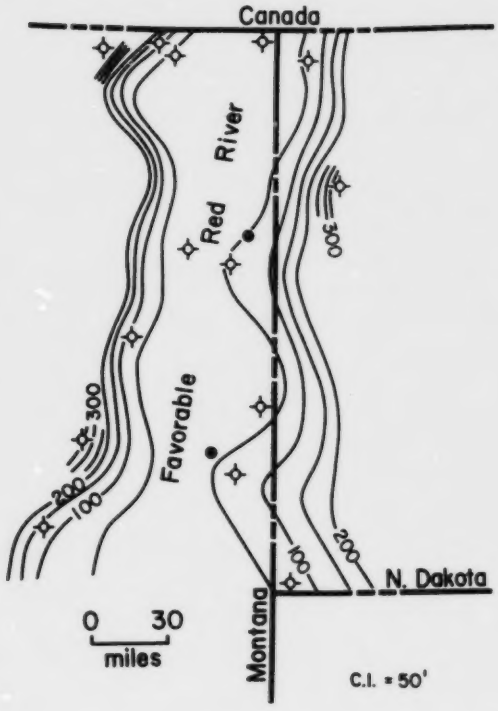


Fig. 7 Contour map of Oil Column required for a 50 per cent oil saturation in the third porosity of the Ordovician Red River. A fairway of favorable reservoir rock lies inside the 100' contour.

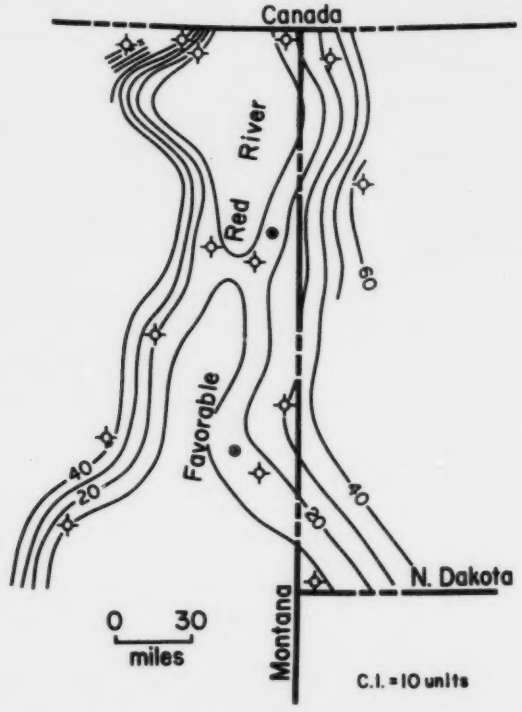


Fig. 6 Contour map of Reservoir Grade from the third porosity of the Ordovician Red River. A fairway of favorable reservoir rock lies inside the 20 units contour.

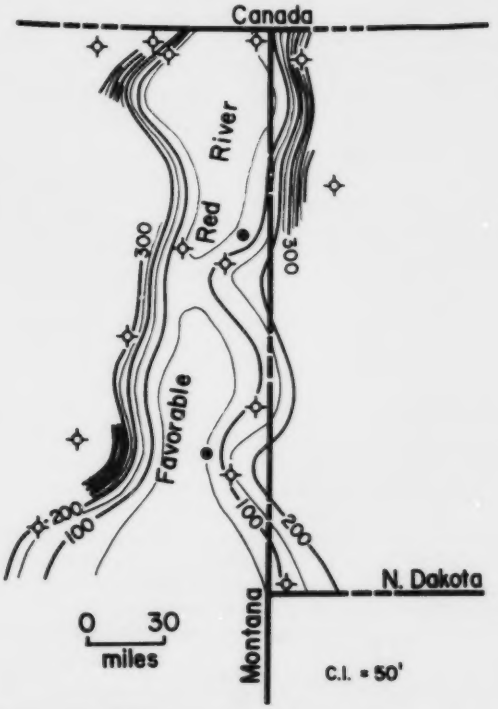


Fig. 8 Contour map of Oil Column required for a 75 per cent oil saturation in the third porosity of the Ordovician Red River. A fairway of favorable reservoir rock lies inside the 100' contour.

provide a first step toward regional evaluation from which selected areas can then be chosen to concentrate further exploratory efforts.

The following is a short explanation about each of the four maps generated in the study:

PORE THROAT SORTING (Fig. 5): Favorable Red River rock was contoured using a cutoff value of 1.5. Values between 1.5 and 2.0 were considered to be fair to marginal while those greater than 2.0 were considered to be poor.

RESERVOIR GRADE (Fig. 6): A reservoir grade value of 20.0 was used as the cutoff for favorable Red River reservoirs while values between 20.0 and 40.0 define an area of fair to marginal reservoirs. Values greater than 40.0 represent rock with low reservoir potential.

OIL COLUMN REQUIRED FOR A 50 PER CENT OIL SATURATION (Fig. 7): A cutoff value of 100 feet was used to define favorable Red River rock. Values between 100 and 200 feet define the area of fair to marginal rock while values greater than 200 feet represent poor quality rock. A 50 per cent oil saturation was used because, as a generalization, reservoir rock will not produce economic quantities of oil until approximately 50 per cent of the available porosity is oil saturated. This is only a "ball park" figure and, if conditions or experience should dictate otherwise, oil columns could be calculated to reflect a more appropriate oil saturation. The contours on the map thus represent the minimum oil columns or trap closures required before marginal oil production can be expected.

OIL COLUMN REQUIRED FOR A 75 PER CENT OIL SATURATION (Fig. 8): The same oil column cutoffs for good, fair and marginal rock were used as in the 50 per cent oil saturation map. A 75 per cent oil saturation represents the level of saturation which should yield good economic recoveries of oil. The contoured fairways are narrower than in the 50 per cent oil saturation map because of the higher 75 per cent minimum oil saturation. This reflects the higher reservoir quality of the rock.

The data delineate a north-south trending fairway and when compared to a lithology map by Foster (1972), reservoir quality appears to be associated with dolomitization. The best reservoir rock possesses a dolomite content ranging from 40 to 80 per cent with reservoir quality dropping off in areas of less than 40 per cent or greater than 80 per cent dolomite. This may be evidence for enhanced porosity and permeability as a function of optimum dolomitization. Dolomite within the Red River is a result of secondary processes (Foster, 1972) and it has long been recognized that primary limestone porosity and permeability can be enhanced by dolomitization (Levorsen, 1954). Evidence from capillary pressure data infers that when the dolomite content exceeds 80 per cent, dolomitization becomes destructive resulting in a reduction of the porosity and permeability. By correlating capillary pressure data with stratigraphy, it is possible to measure the effects of dolomitization and identify a fairway exhibiting the best reservoir potential. It should be noted that a number of dry holes are present within the favorable fairway trend. The quality of the rock in these wells was good but unfortunately either a trap was not present or petroleum never migrated into these areas.

Other than identifying an area possessing favorable reservoir rock, what other capillary pressure applications are available to the explorationist? Geophysical prospecting is popular in the Williston Basin and a direct application of oil column heights can be used. If a particular area of interest requires a minimum of 100 feet of trap closure then seismic data need only be tuned to detect structures of this magnitude. This can eliminate costly reprocessing and provide constraints for analyzing seismic data or when acquiring new data. Ranking prospects is a valuable application. It is common for the explorationist to generate a number of prospects of which only a few can be drilled. Regional capillary pressure maps may also be used to help select the best prospects for first consideration. Other uses might be in developing more accurate effective porosity maps or, in the case of stratigraphic traps, mapping displacement pressure oil columns to determine the downdip limit of oil accumulations.

SUMMARY

Mercury injection capillary pressure data can be integrated into many phases of exploration and development geology. They directly measure petrophysical properties which can be used to evaluate reservoir quality, calculate oil columns and determine minimum trap closures required for economic oil production. A capillary pressure study of the Ordovician Red River is one example of how capillary pressure techniques can be applied to identify areas of favorable reservoir rock. Maps of pore throat sorting, reservoir grade and oil columns for 50 per cent and 75 per cent oil saturation delineate a north-south trending fairway along the North Dakota-Montana border. Evaluation of the maps indicates reservoir rock quality to be influenced by dolomitization. The parameters identified by these maps can then be used to focus exploration and fine tune other oil finding methods.

REFERENCES CITED

Foster, N. H., 1972, Ordovician System. In: Geologic Atlas of the Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, Colorado, pp. 76-85.

Levorsen, A. I., 1954, Geology of Petroleum: W. H. Freeman and Company, San Francisco, pp. 126-128.

Purcell, W. R., 1949, Capillary pressures — their measurement using mercury and the calculation of permeability therefrom: AIME Petroleum Transactions, v. 186, pp. 39-48.

Schowalter, T. T., 1979, Mechanics of secondary hydrocarbon migration and entrapments: AAPG Bull., v. 63, pp. 723-760.

Smith, D. A., 1966, Theoretical considerations of sealing and non-sealing faults: AAPG Bull., v. 50, pp. 363-374.

Stout, J. L., 1964, Pore geometry as related to carbonate stratigraphic traps: AAPG Bull., v 48, pp. 329-337.

HYDRODYNAMIC TRAPPING IN MISSION CANYON RESERVOIRS: ELKHORN RANCH FIELD, NORTH DAKOTA

WILLIAM D. DeMIS

Consultant
Denver, Colorado

ABSTRACT

Hydrocarbons in Mission Canyon reservoirs in the Elkhorn Ranch field area are trapped by hydrodynamic flow of waters downdip and to the northeast. The Elkhorn Ranch field is located on a north-plunging anticline with only very minor crestal closures. Mission Canyon production is localized on the north and northeast side of the structure. Subtidal/strandline facies of the Mission Canyon, as defined by anhydrite and porosity isopachs, trend south-southwest across the plunge of the structure at a very low angle, so low as to preclude trapping by stratigraphic pinch-out.

The lower Mohall, upper Mohall, and Sherwood porosity intervals of the Mission Canyon are all productive within the field. Each has a unique distribution of oil production, but the apparent oil-water contact for each zone is tilted the same direction and amount. Plots (3 cycle, semi-log) of porosity versus core-derived permeability data for the upper and lower Mohall porosities show a linear relation above a threshold of about 12 percent porosity, below which no permeability (<1 md) exists. The Sherwood has an empirically-determined effective cut-off of 8 percent. The configuration of structure and porosity pinch-outs (and permeability barriers defined from the core data) for these productive intervals does not provide a hydrocarbon trap. Tilt of the oil accumulation appears to be in the order of about 25 feet per mile to the northeast. Tilts of oil-water contacts determined for the Elkhorn Ranch field are consistent with tilts for the Billings Nose field (Berg and Mitsdarffer, 1986).

A regional map of formation water salinity shows a region of fresher waters south and southwest of the field. A regional potentiometric map constructed using Horner-plot extrapolated shut-in pressures, and corrected for salinity variations, shows a tilt of about 60 feet/mile to the northeast of the Elkhorn Ranch field. The calculated tilt of the oil column is 150 ft/mi, while the observed tilt is one-sixth of that gradient. This discrepancy may result from the field not having reached equilibrium with the invading waters, a conclusion first stated by Berg and Mitsdarffer (1986) for Billings Nose.

Exploration and production geologists may be able to expand their prospects by incorporating this hydrodynamic model into their Mission Canyon play concepts.

INTRODUCTION

The Mission Canyon reservoirs of west-central North Dakota include two giant oil fields (>100 million barrels recoverable): Little Knife field and Billings Nose area (McCaslin, 1987), as well as several other prolific fields such as the Rough Rider and the Elkhorn Ranch-Anderson Coulee areas (Fig. 1).

The trapping mechanism for oil accumulations in Mission Canyon oil fields has been interpreted to be a stratigraphic pinch-out across a structural high. The facies change involves an up-dip change from porous, subtidal skeletal mudstones and wackestone to tight, anhydritic, sabkha flat deposits across an anticline (Lindsay and Roth, 1982; Altschuld and Kerr, 1982). This mechanism is responsible for trapping oil at fields such as Little Knife, but it is not operative in all Mission Canyon fields. In particular, the Elkhorn Ranch-Anderson Coulee area (herein called Elkhorn Ranch) does not fit this simple model. This paper demonstrates that hydrodynamics is the principal trapping mechanism for the Elkhorn Ranch field by showing that the configuration of the structure and the stratigraphy cannot trap hydrocarbons, and by documenting that the oil column within the field, and the potentiometric surface of Mission Canyon Formation waters at the field, are tilted to the northeast.

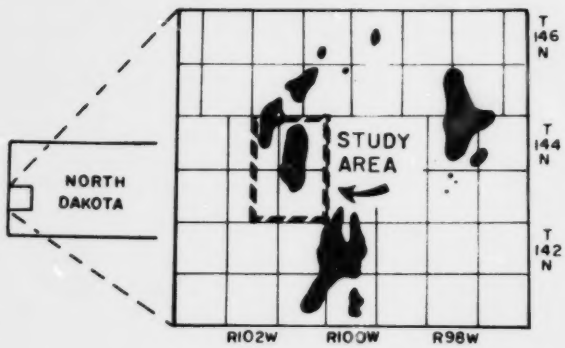


Fig. 1 Location of study area and significant Mission Canyon production.

METHOD OF STUDY

This study is based on data readily available to geologists: electric logs, scout tickets, drill stem test reports, and state production data. Special core analyses, mercury injection profiles, pressure build-up data and other production engineering information were not available. All the cores in the field were described, but the author did not come to any substantially different conclusions on the stratigraphy and facies of the Mission Canyon than those presented by other workers (Lindsay and Roth, 1982; Kupecz, 1984), which would be significant to understanding the nature of the trapping mechanisms.

ANATOMY OF THE FIELD

The Elkhorn Ranch field has produced 11.6 million barrels of oil and 10,682 MMCF gas from 69 Mission Canyon wells since the Mission Canyon reservoir was discovered in 1974. Total field monthly production is now 2500 barrels from 65 wells. Average per well production is 160,000 barrels of oil, and the average well has been producing for 4.58 years

(weighted average). While the first Mission Canyon production in the field was in 1974, most of the field was not developed until the 1980s. Seventy-two percent of the Mission Canyon wells in the field were completed after 1981.

The Mission Canyon Formation of the Elkhorn Ranch field is composed of a series of shoaling-upward cycles superimposed on a larger regressive event. These cycles consist of open marine, skeletal packstones that grade upward into subtidal, dolomitized (porous), skeletal mudstones and wackestones, to intertidal algal stromatolites and supratidal coated grains, micrite, and algal stromatolites infilled with generally nodular anhydrite (Kupecz, 1984). These cycles were repeated several times in the upper Mission Canyon and formed the succession of porosities seen at the field. Individual cycles lack the development of the evaporite facies, except for the last part of the major cycle, during which thick anhydrite was deposited.

The Elkhorn Ranch field is located on a north-plunging anticline with only very minor crestal closures (Fig. 2). Dip of the east flank is steep, whereas the west flank is more gently dipping. The Neutron-Density suite of logs allow for easy identification of high density anhydrite which, when corroborated with sedimentary textures in cores, documents the sabkha facies. Trends of the Mission Canyon anhydrite isopach (State "A" marker to base anhydrite; Fig. 3) derived from petrophysical logs are superimposed on Figure 2. The

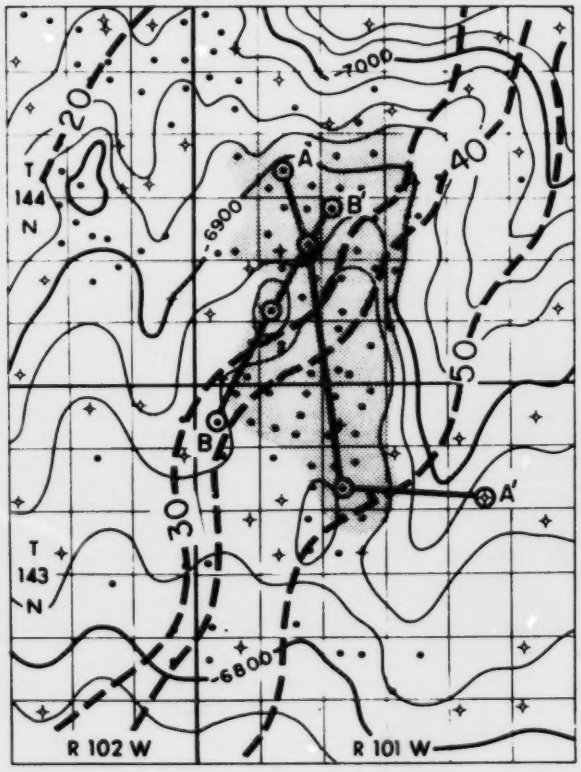


Fig. 2 Mission Canyon structure, Elkhorn Ranch-Anderson Coulee fields (T143 and 144N, R101W). Mission Canyon production is shaded. Dashed lines are net anhydrite isopach (State "A" marker to base anhydrite). Note that depositional facies, as defined by evaporite isopach, strike at a low angle across the structure.

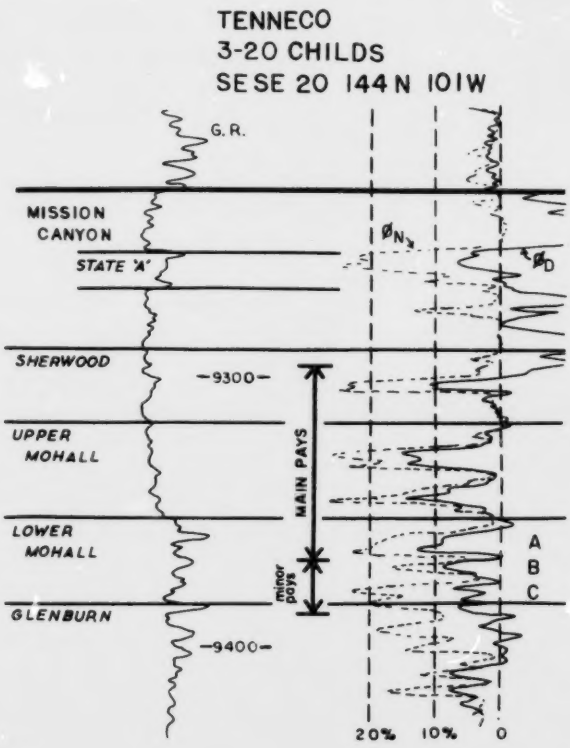


Fig. 3 Type electric log, showing porosity subdivision within the Mission Canyon used in this report.

Mission Canyon sabkha facies strike across the structure at such a low angle that the usually assumed trapping mechanism of up-dip facies change on an anticline is not possible.

Mission Canyon porosities are subdivided into intervals using the nomenclature of Elliot (1982), (Fig. 3). These subdivisions allow individual porosity units to be mapped. Distinction of individual porosities is important because changes in hydrocarbon production can be a function either of changes in reservoir quality or of hydrodynamics (Coalson and others, 1986). The two effects can only be distinguished by mapping each unit separately.

Three main porosity units are productive: lower Mohall, upper Mohall, and Sherwood. The lower Mohall is informally subdivided into "A", "B", and "C" because of varying production. The "A" interval is the main pay in the lower Mohall. The "B" and "C" porosities are productive in scattered places associated with the "A" porosity.

Cross section A-A' (Fig. 4) shows the overall regressive nature of the upper part of the Mission Canyon. The porosity zones grade up-dip into anhydrite: an occurrence which has led some authors to believe that the trap is stratigraphic (Altschuld and Kerr, 1982).

Cross section B-B' (Fig. 4) is drawn parallel to depositional strike defined by anhydrite isopachs. Very little change is seen in the facies which reinforce the observations made on Figure 2: facies trend southwest across the structure at a low angle.

The structurally highest well in cross section B-B', Nucorp 6-1 Federal, tested the Sherwood porosity and recovered 280 bbls of mud-cut salt water. A test of the porosity in the upper

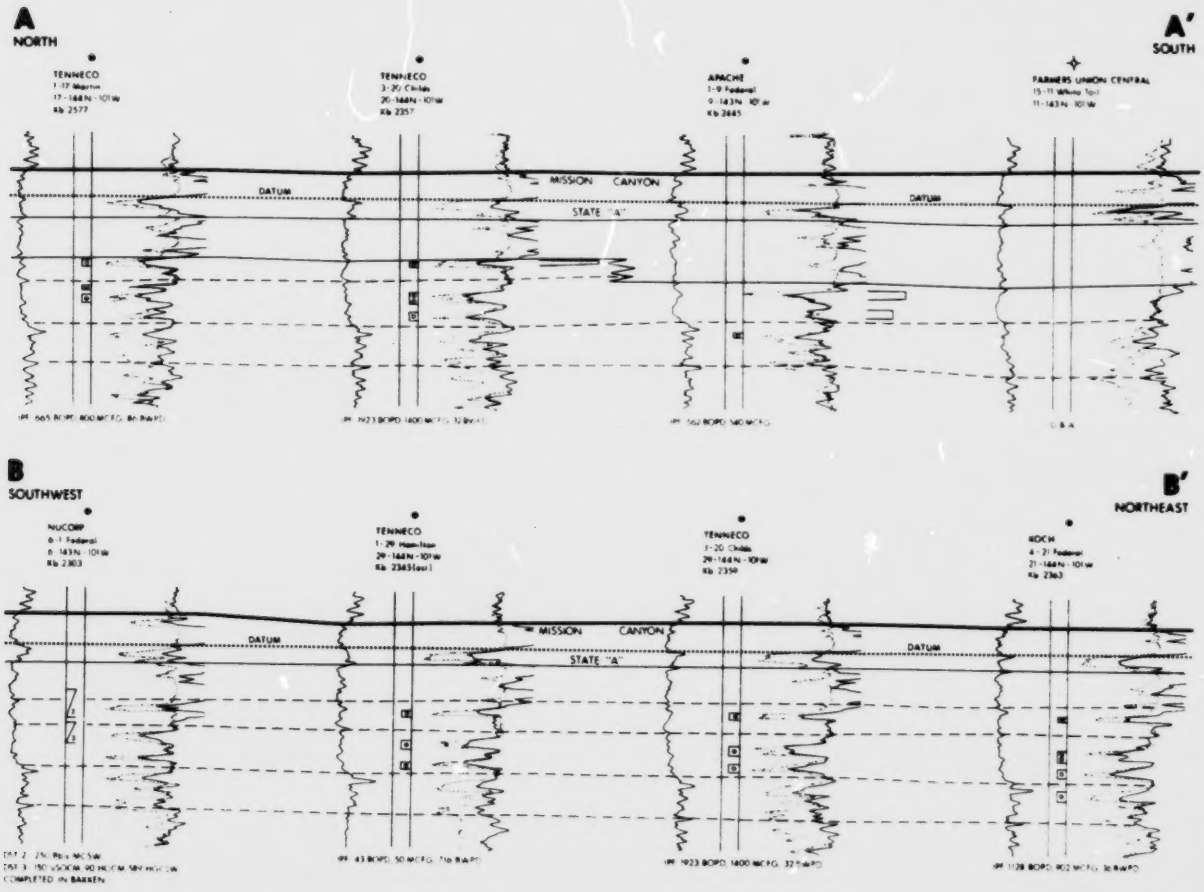



Fig. 4 Cross sections across Elkhorn Ranch field. Cross section A-A' drawn parallel to depositional dip. Stipple pattern shows where porosities pinch out. Cross section B-B' is drawn parallel to depositional strike and shows very little facies changes.

Mohall also recovered a high percentage of water and mud. The Tenneco 1-29 Hamilton well was completed in these two zones, but with a high percentage of water. Wells to the north on this cross-section are completed in successively lower zones, even though they are down-dip, which indicates that the entire oil column is tilted to the northeast. It is assumed that there is one common oil column in the field. Productive reservoir rock is separated by non-sealing tight carbonate.

One may argue that the apparent tilt to the oil-water contact is merely an artifact of a judiciously drawn cross section. A series of porosity maps will be presented to show in three dimensions that the facies alone cannot account for the trapping of hydrocarbons in this field.

POROSITY MAPS

A plot of porosity versus permeability for the upper and lower Mohall porosities is based on all cores cut through these zones (Fig. 5). These data show a linear relation between porosity and permeability above about 12 percent porosity. Most rocks with less than 12 percent porosity have very little permeability (< 1.0 md). Rocks with less than 12 percent porosity are in what is termed the waste zone of the reservoir (Arps, 1964). Even though such porosities may be in the oil column, they will produce only water, or a very low percentage of oil, due to capillarity of the rock.

Pore-throat sorting also effects the ability of a reservoir to produce oil (Coalson and others, 1986), but unfortunately, no information is available to determine the sorting of the pore throats. However, empirical observations within the field substantiate a 12 percent porosity limit. Rocks with less than 12 percent porosity in the lower Mohall "A" and upper Mohall zone are not capable of production, even though wells all around them are productive.

Figure 6 shows an isopach of the lower Mohall "A" zone with greater than 12 percent porosity. This zone is porous across the field. The "A" porosity pinches out 15 miles to the southeast at the Big Stick field (Altschuld and Kerr, 1982, Fig. 16; Mitsdarffer, 1985).

Figure 7 shows the isopach of the upper Mohall zone with greater than 12 percent porosity. This porosity has a peculiar "tight" region that extends across the field, parallel to the structure. It would be tempting to call this a tidal channel which has cut out the reservoir, but the reader is reminded that it is merely an artifact of the high porosity cut-off: a greater-than-six-percent porosity isopach map would not show the "tight" region. Also, the trend of this "tight" zone is parallel to the facies trends. Tidal channels form perpendicular to the strand line. The "tight" region is probably the result of a subtle difference in diagenesis along the crest of this structure.

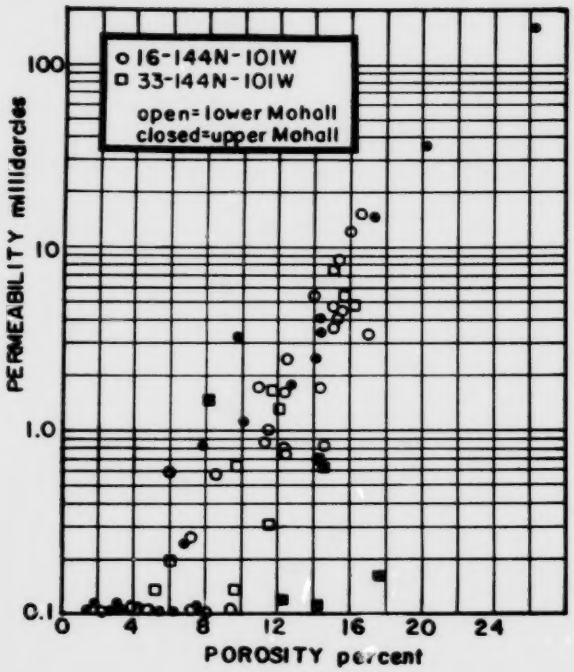


Fig. 5 Relationship of porosity to permeability in the upper and lower Mohall intervals based on cores from Elkhorn Ranch field. Permeability generally becomes linear with respect to porosity above about 10 to 12 percent.

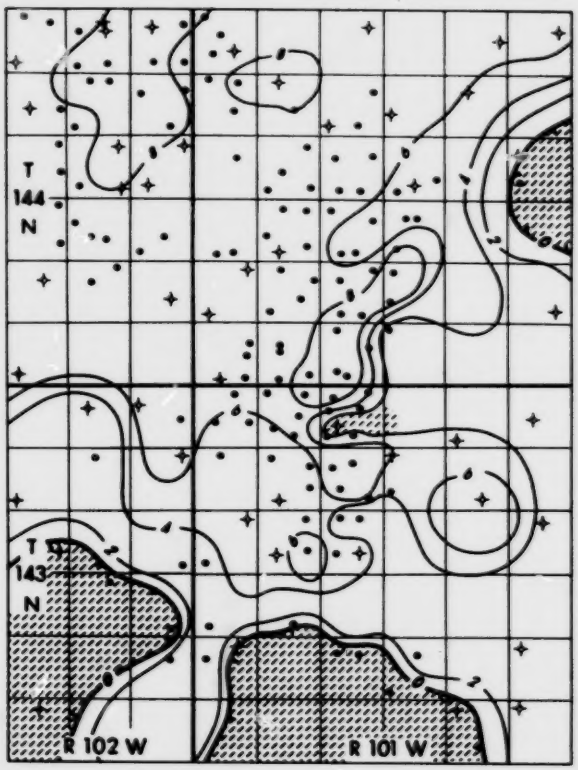


Fig. 6 Isopach map of lower Mitchell "A" porosity greater than 12 percent. Contour interval is two feet. Diagonal dash pattern is tight region. Note that porosity does not pinch out near the field.

Only one core is available for the Sherwood porosity. The data are summarized in Table 1. These data show that there is a very significant "thin-bed" effect on the electric logs. On the logs, the zone appears to be three feet thick with 13 percent porosity, but core-derived data show higher porosity, up to 22 percent, and four feet of porous rock. Due to the large discrepency in the core versus log porosities, a mappable core-derived porosity cut-off can not be established. An empirical cut-off of 8 percent was established by review of the field production. A porosity isopach map was constructed using this cut-off, with the understanding that it is pessimistic, due to the "thin bed" effect.

The Sherwood porosity isopach map (Fig. 8) shows a southwest trend which is roughly parallel to the anhydrite isopach. This zone does pinch out across the plunge of the structure, but at such a low angle that it should not be able to hold oil.

Table 1 List of core- and log-derived porosity and permeability data for Sherwood porosity from Tenneco 1-33 USA-UVI, section 33, T144N-R101W.

Depth (corrected)	Porosity (%) Log	core	Permeability (md)
9297	7.5	20.4	0.75
9298	5.25	0.5	8.5
9299	3.5	4.3	0.178
9300	13.5	19.8	2.8
9301	13.0	16.5	9.9
9302	7.5	22.8	27.0

Neither Figure 6 or 7 show an effective pinch-out parallel to the trend of the anhydrite which is the point of this paper. Production at the Elkhorn Ranch field is not controlled by a stratigraphic facies pinch-out. In the case of the lower Mohall "A", the actual facies change into tight evaporites is 15 miles to the south. While the Sherwood porosity does pinch out in the vicinity of the field, the configuration of the tight line and the structure can not trap oil under hydrostatic conditions.

NATURE OF THE TRAP

Figures 9, 10 and 11 show the distribution of hydrocarbon production for each porosity zone with the effective tight line superimposed on the structure map. Maps of the lower and upper Mohall production show dramatically that the oil column is tilted off the structure. The "A" zone of the lower Mohall (Fig. 9) is uniformly porous across the field, yet production is located on the east side only, and far down-dip to the north and northeast. The tight zone in the upper Mohall (Fig. 10) could trap oil on the east side of the field, but oil in the north part of the fields should drain out up-dip and out of the structure.

Even production from the Sherwood porosity, which pinches out across the structure, cannot be explained as a stratigraphically trapped accumulation. The oil should migrate updip and out of the structure to the southwest (Fig. 11). A potentiometric surface tilted to the northeast forms the trap on the southwest side of the field.

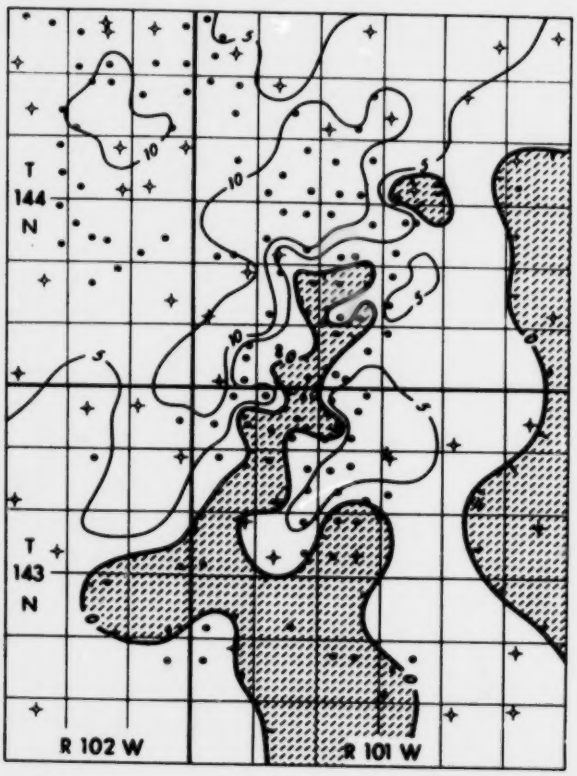


Fig. 7 Isopach of upper Mohall porosity greater than 12 percent. Contour interval is five feet. Diagonal dash pattern is tight region. Note that tight region is not parallel to facies trends.

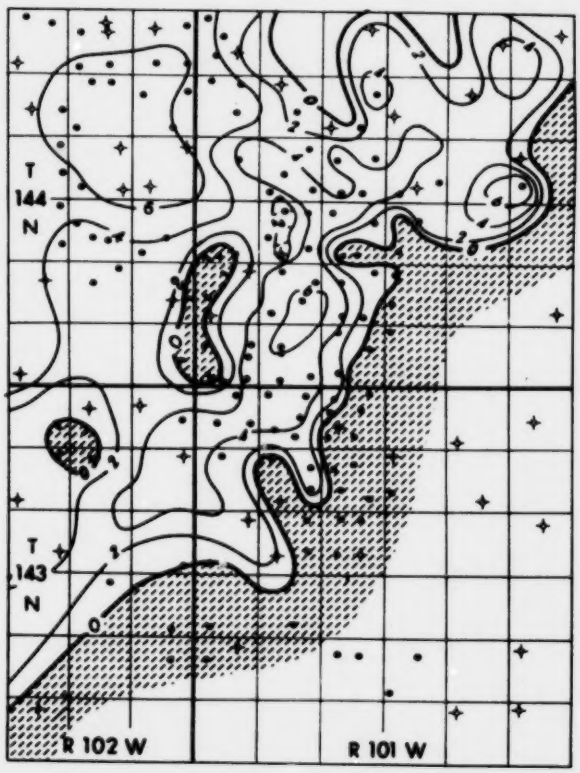


Fig. 8 Isopach of Sherwood porosity greater than 8 percent. Contour interval is two feet. Diagonal dash pattern is tight region. Note that porosity trends to the southwest, roughly parallel to anhydrite contours.

Viewed in total, the productive limits of each of the zones show a single oil column tilted about 25 feet per mile to the northeast. Note that the western limit of production for each successively lower porosity zone is shifted to the east: a confirmation in three dimensions of the tilted oil column shown on cross section B-B'.

The tilt of the oil columns for each porosity zone is only approximated by the maps. A map of the actual oil-water contact could not be much more refined. In rocks with low permeability, the transition from oil-free water to water-free oil is gradational (Arps, 1964). This fact, compounded by the lack of a vertically continous reservoir, makes picking the actual oil-water contact very difficult, and subjective.

POTENTIOMETRIC SURFACE

A map of the salinity of recovered formation water from drill stem tests around Elkhorn Ranch is shown in Figure 12. In general, there is a wide variation in the data. Salinity varies by more than 50,000 ppm within one township, and sometimes by more than 50,000 ppm in one well. The variation in the data is ascribed to lateral discontinuity between, and heterogeneity within, Mission Canyon porosities. There is a regional trend in the data from lower salinity in the southwest to higher salinity in the north and northeast. The salient of low salinity in T143N-R102W is interpreted to indicate fresh water invasion along the trend of more porous facies.

Drill stem test pressures were compiled for the region around the field. Recorded pressures were extrapolated to a true pressure using Horner plot analysis. These data were filtered for bad tests, as well as tests which experienced drawdown near the fields. From these pressure data, a map of the potentiometric surface was constructed (Fig. 13), with a correction for the regional variation in salinity, using equivalent brine densities given in Dahlberg (1982). This map shows that the potentiometric surface is tilted 60 feet per mile to the northeast in the region of the Elkhorn Ranch field. Using oil and water densities of 0.625 g/cm^3 and 1.028 g/cm^3, respectively, the tilt amplification factor is 2.55. The calculated tilt of the oil-water contact is 150 ft/mi. This is more than six times the observed tilt of about 25 feet per mile as derived from the maps presented above.

DISCUSSION

Tilt of the oil column at Elkhorn Ranch is roughly the same amount and direction as that derived for Billings Nose (Berg and Mitsdarffer, 1986). Mitsdarrfer (1985) has shown that there is a plume of fresher water south and west of the Billings Nose field and that the oil column is tilted to the northeast 25 feet per mile. He has also shown that the calculated potentiometric surface relative to the densities of the formation waters is tilted to the northeast about 50 feet per mile. Calculated tilt at the Billings Nose field is about 127 ft/mi, a discrepancy

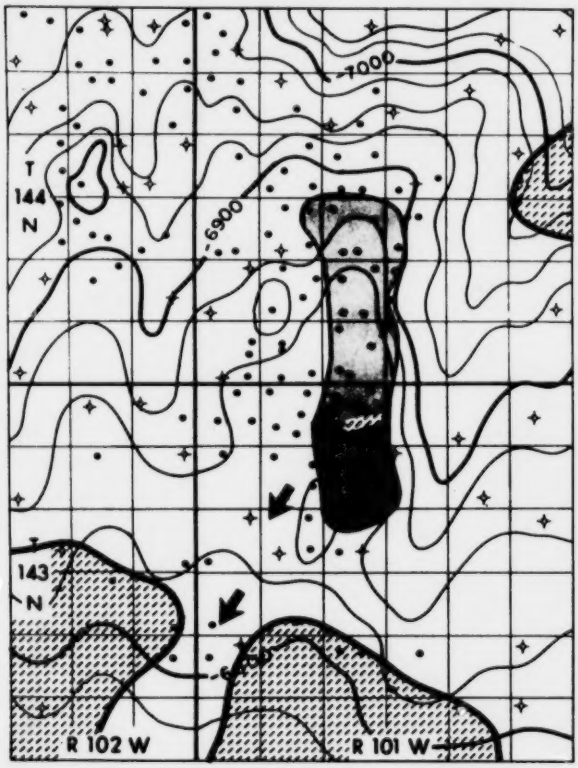


Fig. 9 Map of lower Mohall "A" porosity production (shaded) superimposed on Mission Canyon structure with tight region (from Fig. 6). Note that production is tilted to the east and down the anticline to the north. Arrows show potential leak points if the system were hydrostatic.

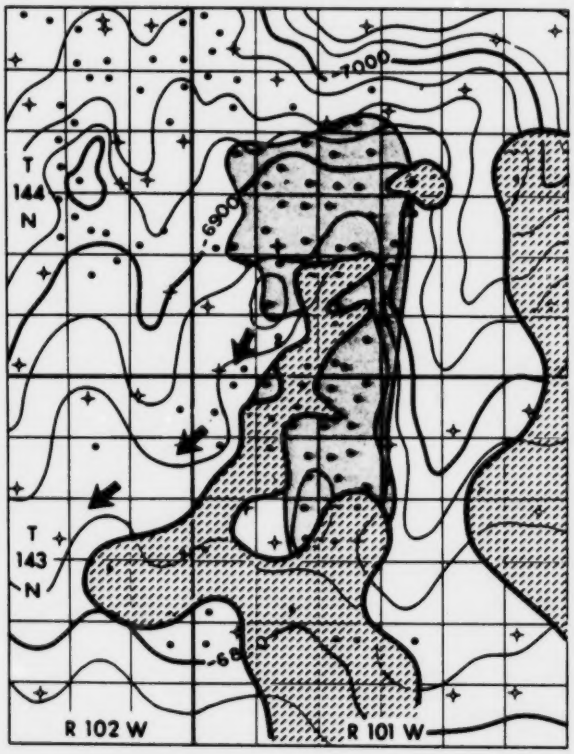


Fig. 10 Map of upper Mohall porosity production (shaded) superimposed on Mission Canyon structure, with tight region (from Fig. 7). The tight region might trap hydrocarbons on the east side of the field, but oil in the north end of the field would leak out (arrows) under hydrostatic conditions.

similar to the Elkhorn Ranch field. Mitsdarffer (1985) concludes that the oil at the Billings Nose field accumulated under a regime of lower potentiometric gradient in the past and has not yet equilibrated to the higher tilt of the present day. The same explanation seems likely for the Elkhorn Ranch field.

Downey (1984) has shown that the Mission Canyon aquifer is active across the northern plains, and across the Williston Basin. In the Billings County portion of the Williston Basin, Downey shows that the potentiometric surface is tilted east. Both this report and the work of Mitsdarffer document that the potentiometric surface is tilted more to the northeast. The difference is probably due to the scale of the maps and resolution of the data.

An alternative interpretation for the unique oil production at the Elkhorn Ranch field is that it is the result of subtle and unmappable changes in pore throat sorting and geometry, similar to the traps reported by Schowalter and Hess (1982). Such an explanation is improbable because: 1) the apparent tilt of hydrocarbon production for each porosity zone is approximately the same amount and direction; 2) each successively lower zone is productive farther to the northeast, as would be predicted with a single, tilted oil column; 3) observed oil column tilt is the same direction as that predicted by the potentiometric map, and; 4) tilt of the oil column at the Elkhorn Ranch field is similar to the tilt reported for other Mission Canyon fields. In the absence of information on pore throat sorting and capillarity, the alternative interpretation cannot be verified, only dismissed as improbable.

One of the implications of this research is that hydrodynamic flow must have occurred during oil migration. The time of maximum oil maturation and migration is early Tertiary (Webster, 1984). Berg and Mitsdarffer (1986) state that hydrodynamics only assisted a stratigraphic trap. No stratigraphic trapping of any kind can be found for over half of the trapped oil at the Elkhorn Ranch field. On the basis of this report, it would appear that a hydrodynamic regime existed at the time of oil migration. Therefore hydrodynamics probably occurred during oil migration in the early Tertiary.

One could argue that the oil collected elsewhere and was trapped during a later remigration event precipitated by a change in hydrologic conditions. If that is the case, then a large, presently flushed, structural and/or stratigraphic trap should exist southwest of the field which is capable of trapping under hydrostatic conditions.

Incorporation of hydrodynamics into Mission Canyon play concepts, even only as a modifier to ordinary play concepts, does have significant implications for exploration and production geologists. First, primary recoveries of hydrocarbons are much higher with a strong water drive than with the usual, gas-depletion recovery factor. Second, exploration prospects need not demonstrate a porosity pinch-out that cuts across an

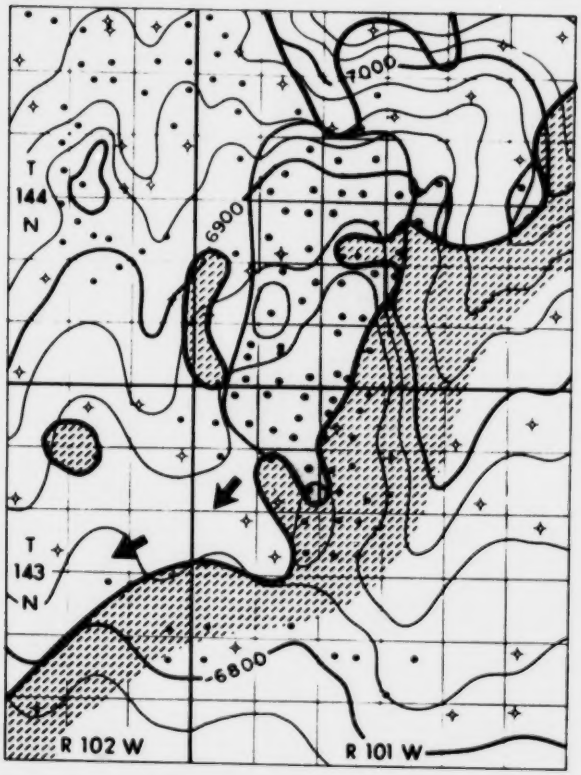


Fig. 11 Map of Sherwood porosity production (shaded) superimposed on Mission Canyon structure map, with tight region (from Fig. 8). The configuration of the tight line and the structure can not explain the accumulation. Oil would leak out (arrows) under hydrostatic conditions.

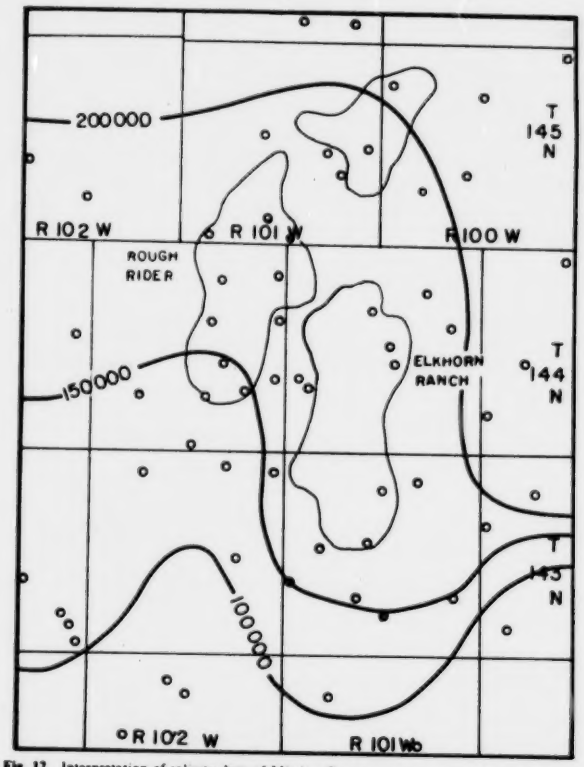


Fig. 12 Interpretation of salinity data of Mission Canyon water recovered from drill stem tests. Circles show control points. Data are listed in Appendix 1.

anticlinal fold axis at 90 degrees to be assured of hydrocarbon trapping. Hydrodynamics can provide an assist to the pinch-out play. Third, production prospects can be proposed which are not possible with horizontal oil-water contacts. Down-dip offsets on the northeast side of producing Mission Canyon wells, provided they are in areas of tilted potentiometric surface, might offer low-risk development prospects.

This report also demonstrates that very high porosity is required for some porosities to have effective permeability. Each porosity interval for the Mission Canyon has its own effective cut-off, which may be much higher than the "traditional" 6 or 8 percent. Prospects which call upon the up-dip pinch-out of ten percent porosity (for the Mohall) into tight rock will only drill into the waste zone of the reservoir.

SUMMARY

The Elkhorn Ranch field is a medium-sized Mission Canyon field which is trapped by hydrodynamics and not by facies change. Effective porosity for the Mohall zones of the Mission Canyon is high (>12 percent). The Sherwood zone shows a significant thin-bed effect; log-derived porosity values for it may be spurious. An empirical effective cut-off for the Sherwood is 8 percent. Individual porosity zones within the Mission Canyon have a unique distribution, but are generally

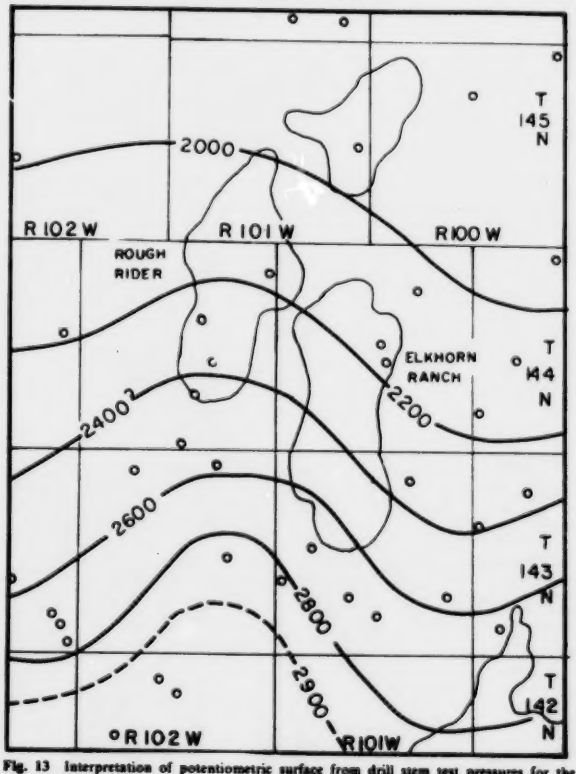


Fig. 13 Interpretation of potentiometric surface from drill stem test pressures for the Mission Canyon. Map is corrected for salinity variations. Circles show control points. Note inclination of the potentiometric surface at Elkhorn Ranch field.

continuous across the field and cannot provide a barrier to hydrocarbon migration. The configuration of Mission Canyon structure and porosity cannot hold hydrocarbons under hydrostatic conditions.

The Mission Canyon Formation contains areas of significantly fresher water south and southwest of the Elkhorn Ranch field. The potentiometric surface of the Elkhorn Ranch field is inclined to the northeast, and probably provides the trapping mechanism for the field.

ACKNOWLEDGEMENTS

This paper is based in part on research initiated at Pennzoil Exploration and Production Company. I would like to thank Pennzoil for permission to publish those ideas. This paper was reviewed by Mary K. Nelis and Tim. T. Schowalter. I thank them for their help.

APPENDIX 1

OPERATOR	WELL	SECTION	SALINITIES	K.B. (ft.)	INTERVAL (ft.)	SIP (extrpltd)
T142N-R101W						
Conoco	8-1	8	148,000	2523	9284-9334	4411
Conoco	15-1	14	65,000	---	9309-9377	---
T142N-R102W						
Dia. Sham.	34-4	4	80,000	2556	9170-9229	4330
			155,000	2556	9390-9504	4402
Dia. Sham	21-9	9	190,000	---	9395-9427	---
Dia. Sham.	11-10	10	50,000	---	9365-9373	---
			60,000	2338	9433-9441	4385
Coastal 1-J		29	---	2641	9435-9469	4451
T142N-R103W						
Shell	24-31	24	68,000	---	9498-9594	--
T143N-R100W						
Al. Aquit.	1-8	8	200,000	2461	9410-9450	4645
			200,000	2461	9452-9490	4459
Gulf	1-18-1A	18	---	2750	9742-9822	4533
Coastal	Y-23-1	23	140,000	---	9582-9636	---
Tenneco	G-1-30	30	---	2612	9489-9571	4440
T143N-R101W						
Samson	1-2	2	160,000	2373	9438-9464	4450
Cenex	12-10	10	165,000	---	9432-9445	---
Apache	4-16	16	130,000	---	9477-9495	---
Chambers	3-19	19	210,000	2375	9300-9369	4408
Chambers	2-27	27	131,000	2480	9365-9425	4435
Chambers	1-28	28	160,000	2416	9244-9340	4438
T143N-R102W						
Cenex	5-1	1	96,000	---	9237-9244	---
Cenex	6-2	2	100,000	2278	9188-9255	4391
			110,000		9253-9280	
Apache	1-5	5	160,000	2155	9092-9142	4390
Al. Aquit.	1	23	107,000	2339	9337-9230	4502
Al. Aquit.	2-31	31	146,000	---	9180-9203	---
T143N-R103W						
Grace	32-22	22	141,000	2471	9295-9331	4338
Dia. Sham.	24-25	25	128,000	2595	9395-9415	4429
Gas Prod.	36-1	36	140,000	2524	9334-9360	4451
Gas. Prod.	Ent. 2	36	---	2470	9267-9283	4352
T144N-R100W						
Patrick	1-4	4	190,000	2472	9818-9864	4512
Amoco	1	20	200,000	2558	9540-9608	4482
Koch	13-30	30	200,000	2615	9599-9633	4422
Jordan	1-1	36	200,000	2592	9730-9763	4509
T144N-R101W						
Florida	7-2	7	142,000	---	9372-9396	---
Florida	1-F	7	142,000	---	9322-9350	---
Cenex	15-9	9	95,000	---	9334-9350	---
Koch	6-11	11	145,000	2328	9412-9441	4412
Amoco	13-1	13	187,000	---	9330-9370	---
Apache	15-13	15	146,000	---	9373-9385	---
Florida	19-2	19	172,000	---	9222-9246	---
Tenneco	1-30	30	150,000	---	9180-9235	---
T144N-R102W						
MGF	44-1	1	---	2308	9325-9345	4358
Apache	2-5	2	120,000	---	9440-9486	---
Supron	1-F	10	128,400	---	9544-9588	---
Unit Drilling	11-12	11	125,000	---	9570-9590	---
Florida	13-1	13	180,000	---	9654-9685	---
Apache	16-3	16	132,000	---	9112-9148	---
Apache	2-23	23	140,000	2176	9136-9156	4440
Pet. Inc.	1	24	110,000	---	9260-9297	---
Nance Pet.	1-26	26	26,000	---	9393-9407	---
			120,000		9393-9428	---
Axem	7-29	29	90,000	2450	9379-9418	4482
Adobe	14-34	34	65,000	2413	9334-9380	4493
T144N-R103W						
Coastal	1-13	13	175,000	2467	9420-9481	4433
Terra	2-18	18	181,000	---	9200-9300	---
T145N-R100W						
Amoco	1	1	---	2442	9679-9687	4519
Belco	2-1	1	172,000	2445	9633-9712	4390
Belco	3-5	7	200,000	---	9790-9806	--
Meridian	13-10	10	190,000	---	9470-9523	---
Gulf	1-21-3D	21	200,000	---	9550-9617	---
T145N-R101W						
Belco	1-16	16	167,000	2424	9520-9556	4347
Koch	16-23	23	215,000	---	9426-9452	---
Milestone	44-23	23	190,000	---	9528-9578	---
Union	24-1	24	170,000	2441	9540-9596	4427
Sage	44-31	31	200,000	---	9420-9461	---
Milestone	33-33	33	172,000	---	9160-9230	--
Belco	14-34	34	171,000	---	9268-9306	---
T145N-R102W						
Milestone	34-19	19	178,000	2655	9652-9742	4433
Pennzoil	27-13	17	182,000	2569	9191-9300	4473
T146N-R100W						
Pennzoil	28-14	28	215,000	---	9711-9800	---
T146N-R101W						
Basic E. S.	1-34	34	200,000+	2171	9336-9364	4471
Belco	2-36	36	130,000	2256	9458-9490	4498

REFERENCES

Altschuld, N. and S. D. Kerr, Jr., 1982, Mission Canyon and Duperow reservoirs of the Billings Nose, Billings County, North Dakota; In: J. E. Christopher and J. Kaldi (eds.), Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication no. 6, p. 103-112.

Arps, J. J., 1964, Engineering concepts useful in oil finding: AAPG Bull., v. 48, p. 157-165.

Berg, R. R., and A. R. Mitsdarffer, 1986, Effects of hydrodynamic flow on carbonate stratigraphic trap, Mission Canyon Formation, Billings Nose, North Dakota: AAPG Bull., v. 70, p. 564.

Coalson, E. B., D. J. Hartman, and T. T. Schowalter, 1986, Exploration Petrophysics, Rocky Mountain Short Course Notes: Rocky Mountain Assoc. of Geologists, Denver, Co.

Dahlberg, E. C., 1982, Applied Hydrodynamics in Petroleum Exploration: Springer-Verlag, New York, N.Y., 161 p.

Downey, J. S., 1984, Geology and hydrology of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geol. Surv. Prof. Paper 1273-G, 152 p.

Kupecz, J. A., 1984, Depositional environments, diagenetic history, and petroleum entrapment in the Mississippian Frobisher - Alida interval, Billings anticline, North Dakota: Colorado School of Mines Quarterly, v. 79, no. 3, 53 p.

Lindsay, R. F., and M. S. Roth, 1982, Carbonate and evaporite facies, diagenesis and reservoir distribution of the Mission Canyon Formation, Little Knife Field; In: J. E. Christopher and J. Kaldi (eds.), Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication no. 6, p. 153-179.

McCaslin, J. C., 1987, U.S. drilling lower in 1987, but majors plan to drill more: Oil and Gas Journal, Jan. 26, p.

Mitsdarffer, A. R., 1985, Hydrodynamics of the Mission Canyon Formation in the Billings Nose area, North Dakota: unpublished M.S. Thesis, Texas A & M Univ., 162 p.

Schowalter, T. T., and Paul D. Hess, 1982, Interpretation of subsurface hydrocarbon shows: AAPG Bull., v. 66, p. 1302-1327.

Webster, R. L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota; In: J. Woodward and others (eds.), Hydrocarbon source rocks of the greater Rocky Mountain Region, Rocky Mountain Assoc. of Geologists, Denver, Co., p. 57-81.

HABITAT OF SHERWOOD OIL, RENVILLE COUNTY, NORTH DAKOTA

MICHAEL L. HENDRICKS[1], BRUCE P. BIRGE JR.[2] AND JAKE D. EISEL[3]

[1] *Hendricks and Associates, Inc.*
Denver, Colorado

[2] *Independent Geologist,*
Aurora, Colorado

[3] *Eisel Consulting,*
Lafayette, Colorado

ABSTRACT

The Sherwood beds of the Mission Canyon Formation (Madison) in Renville County, North Dakota, are part of an overall shallowing-upward regressive carbonate and evaporite sequence. Four Sherwood depositional trends are aligned parallel to depositional strike. From east to west these trends are: salina-sabkha, shoreline-lagoon, island-shoal, and open shelf. Productive lithofacies in the shoreline-lagoonal trend are peloidal and intraclastic wackestones and packstones with secondary vuggy porosity. The trap is an updip facies change to impermeable carbonates and anhydrites. Two productive lithofacies characterize the island-shoal trend: algal wackestones and packstones with fenestral and vuggy porosity, and coated-grain packstones and grainstones with interparticle and vuggy porosity. Lateral and updip traps are formed by carbonate mudstones deposited in lagoons and in very low-energy, mud-dominated "channels".

An increase in depositional slope just basinward of the facies change from anhydrite to carbonate favored development of shoals and islands. A general thickening of Sherwood beds accompanies this break in slope.

The modern Trucial Coast in Abu Dhabi resembles the ancient Sherwood depositional system. However, the orientation and composition of Sherwood islands differ from the Abu Dhabi islands. Sherwood islands are highly elongate in a dip direction because of the influence of northeast-southwest oriented paleostructures, very low wave and tidal currents, and the direction of the prevailing winds. Compositionally, Sherwood islands contain more carbonate grains and less mud than their Abu Dhabi counterparts.

Sherwood production can be prolific as demonstrated by individual wells in the Sherwood Field. High production rates in the Smith Field should stimulate more Sherwood exploration along the northeast flank of the basin.

INTRODUCTION

The recent discovery of Smith Field, Renville County, North Dakota has again focused attention on the Sherwood beds of the Mission Canyon Formation along the northeast flank of the Williston Basin. Interest in the Sherwood has increased with a better understanding of the facies relationships of these beds. Depressed oil prices also make shallow Sherwood potential appealing.

This paper will discuss an area of Sherwood production approximately bounded by T160-164N, and R84-86W (Fig. 1), Renville County, N.D.

Fig. 1 Location map showing Sherwood production in Renville County, North Dakota.

GENERAL GEOLOGY

STRUCTURAL SETTING

The northeastern flank of the Williston Basin gently dips ¼ to ½ degree per mile to the southwest toward the present synclinal axis of the basin. Small-scale folding along the northeast flank of the basin has produced a series of southwest-plunging anticlines and synclines. Present structural trends in this part of the basin are similar to those that existed during Mission Canyon deposition. The basin center at that time (Fig. 2) was just west of the present southern axis of the Nesson Anticline (Lindsay, 1985).

Pre-existing structures along the northeast flank were probably reactivated during the Laramide Orogeny, but the structural configuration of this part of the basin was not significantly changed.

Structure, although important in controlling depositional setting and lithofacies trends, is not the primary factor in trapping Mission Canyon oil. Subtle stratigraphic changes along and across structural trends have a more direct influence on reservoir development and trap configuration.

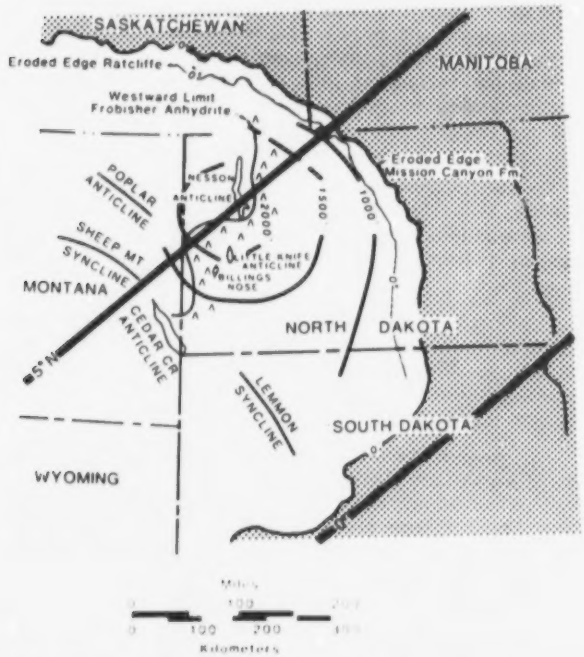


Fig. 2 Index map of the Williston Basin showing significant depositional and erosional limits for Mission Canyon and Ratcliffe beds. From Lindsay, 1985, p. 220.

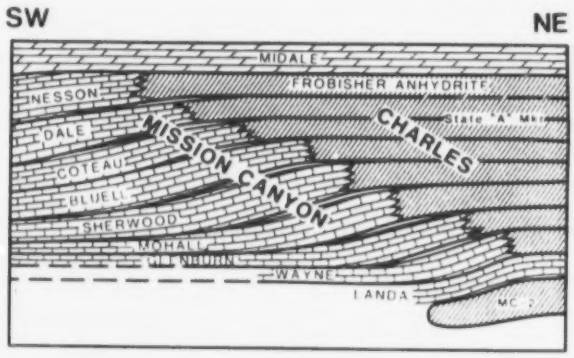


Fig. 3 The regressive beds of the Mission Canyon Formation along the northeast flank of the Williston Basin. From Voldseth, 1986, p. 26.

STRATIGRAPHIC SETTING

Upper Mission Canyon strata along the northeastern flank of the basin were deposited in low-energy subtidal, intertidal, and supratidal environments. These strata were deposited along the eastern margin of the early Mississippian Cordilleran Seaway. Regional lithofacies maps of the Osagean Series (Procter and McCauley, 1968) reveal that the Williston Basin was located in a shallow embayment between the Canadian Shield to the north and the Transcontinental Arch to the south (Stratigraphic Atlas of North and Central America, 1975).

The upper Mission Canyon Formation is a series of shallowing-upward carbonate to evaporite sequences which have informally been subdivided into beds (Harris et al, 1966; Voldseth, 1986). The offlapping or regressive nature of these beds is shown in Figure 3.

The Sherwood beds were named for a sequence of carbonates and evaporites bounded by the underlying sandy dolomites of the Mohall marker and the overlying "argillaceous" dolomites of the Sherwood marker. The beds were first named for productive Mission Canyon beds in the Sherwood Field, Renville County.

Sherwood deposition, along the northeast flank of the basin, occurred in near-shore carbonate and evaporite environment Previous workers (Harris et al, 1966; Malek-Aslani, 1971) described some of these facies relationships and detailed the carbonate to anhydrite changes associated with shoreline fields (Elmore, Mouse River Park, Lake Darling, etc.). Many of these fields were discovered in the early 1960s.

Recent field discoveries by BHP Americas (Monsanto) in the McKinney Field and MacMoRan (Petro-Lewis) in the Smith Field show that these fields are structurally and depositionally downdip and spatially removed from anhydrite edges. These new discoveries, together with similar downdip occurrences in the Tolley and Sherwood Fields (discovered in the late 1950s and early 1960s), have provided a new set of data for an expanded depositional model.

REGIONAL CARBONATE FACIES AND DEPOSITIONAL ENVIRONMENTS

Regionally, four Sherwood depositional trends are aligned parallel to depositional strike (Fig. 4). Each trend normally is wide because of the broad and shallow nature of the depositional shelf. Facies changes between trends, however, are surprisingly abrupt, and may have been controlled by increases in depositional slope.

The easternmost depositional trend is characterized by anhydrites and minor dolomites deposited in hypersaline lagoons, salinas, and sabkhas. Sherwood anhydrites are widespread and extend many tens of miles from their western depositional limits, eastward to the Mississippian subcrop.

The next depositional trend immediately west of the anhydrites is the narrowest, typically only 1 to 3 miles wide. The trend is characterized by carbonate mudstones and peloidal wackestones and packstones deposited in highly restricted lagoons. The peloidal wackestones and packstones may be poorly developed low-energy shorelines, washover deposits from downdip shoal-island complexes, or local shoals in lagoons.

The carbonate to anhydrite transition at the eastern limit of this trend has been used to define and map Sherwood "shorelines". Carbonate packstones in this trend are locally productive. Shoreline trends, as defined by the anhydrite edge, change abruptly and protrude basinward or embay. These trends often align with regional lineaments. Anhydritic depositional edges (zero edges) were sensitive to subtle, structurally influenced bathymetic changes and appear to reflect slope breaks controlled by buried Precambrian basement blocks.

Basinward of the lagoons, the next depositional trend is characterized by grain-rich limestones and carbonate mudstones which were deposited along southwest-plunging anticlines and synclines. Low-energy grain shoals and algal buildups, deposited along the crests of anticlines, were periodically emergent as islands. Significant oil production from these lithofacies has been established in Sherwood, McKinney-Tolley, and Smith Fields, and the potential for further discoveries looks promising.

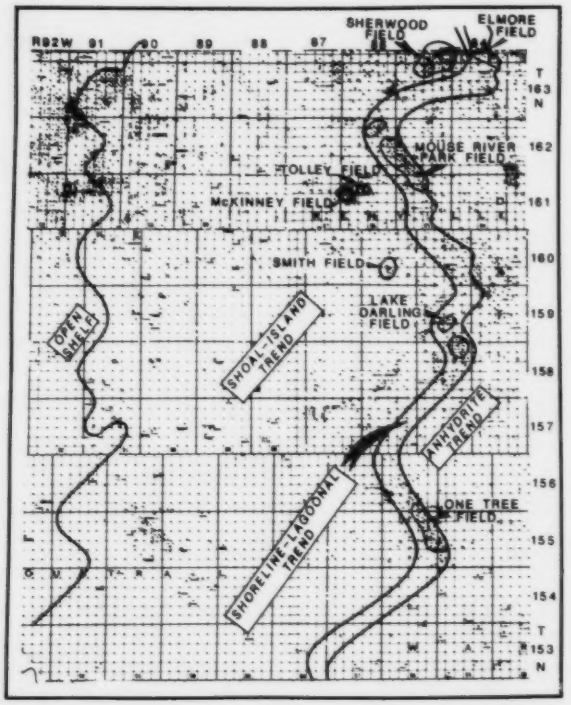


Fig. 4 Major Sherwood depositional facies trends along the northeast flank of the Williston Basin.

Open-shelf environments persisted west of island-shoal trends. Lithofacies of the open shelf are skeletal mudstones and wackestones with crinoid, brachiopod, coral, and bryozoan allochems. The facies change from open shelf to island-shoal parallels the strike of the anhydrite edge, further suggesting an inter-relationship between regional structure and depositional patterns.

SHERWOOD DEPOSITIONAL FACIES

In order to describe the changes associated with productive and non-productive facies, the Shewood beds in Renville County were divided into the three following facies: protected shelf-lagoon, intertidal-supratidal, and salina-sabkha. The open marine lithofacies trend is not present in Renville County.

PROTECTED SHELF AND LAGOON FACIES

Sediments deposited in restricted, low-energy subtidal and lagoonal environments characterize this facies. These sediments can be divided into five prominent lithofacies:

intraclastic wackestones and packstones,
skeletal lime mudstones,
burrowed lime mudstones,
patterned mudstones, and
massively bedded dolomites.

Production from the protected shelf facies occurs in low-energy "shoreline" fields such as Elmore and Mouse River Park, near anhydrite-carbonate facies changes.

Peloidal and intraclastic wackestones and packstones are the principal reservoir facies in shoreline-lagoon fields (Fig. 5). The peloids commonly are partially micritized pieces of *Ortonella* (codiacean algae), as determined from the local presence of discrete nodules of these algae. Intraclasts are of indeterminate origin, but often contain peloids similar to those of the underlying substrate, suggesting possible erosion of partially lithified laminae. Porosity is vuggy and intergranular. Occluding cements are drusy calcite, anhydrite, and baroque dolomite (Fig. 6).

The skeletal lime-mudstone lithofacies contains ostracods, calcispheres, *Ortonella* nodules, and sparse gastropod and brachiopod allochems. Subparallel stratification is rare, and the massive bedding of the unit is probably related to complete bioturbation (Fig. 7A).

The burrowed lime-mudstone lithofacies, which is commonly dolomitic, contains *Chondrites* burrow structures (Fig. 7B). This lithofacies is locally interbedded with the patterned lime-mudstone lithofacies (Dixon, 1976). Patterning in these carbonates is produced by framboidal pyrite (Fig. 7C).

The massively bedded dolomites, which comprise the Sherwood marker, are possibly primary dolomites precipitated in widespread highly restricted lagoons (Fig. 7D). Although highly porous, these beds are impermeable to oil because of extremely small intercrystalline pores. A few miles basinward, these dolomite marker beds become limestones.

INTERTIDAL-SUPRATIDAL FACIES

Sediments deposited in low-energy intertidal environments form the following lithofacies: algal wackestones and packstones and coated-grain packstones and grainstones of the shoal and island facies. Because of local or regional sea-level changes, shoals were periodically exposed. This emergence produced laminated micritic crusts, broken grains, sheet cracks, and teepee structures. These features are rarely observed in the shoreline-lagoon depositional trend to the east.

The algal wackestones and packstones of the shoal and island trend contain dasycladacean algae and codiacean algae dominated by *Girvanella*, *Garwoodia*, and *Ortonella*. Peloids and coated grains are abundant. Fenestrae are normally well developed in this lithofacies, but often are partially to completely occluded by fibrous and drusy calcite spar cements (Figs. 8A and 8B). Reservoir quality can be good when fenestral pores are unoccluded and solution enlarged (Figs. 8C, 8D, and 9).

The coated-grain facies contains ooids, pisoids, peloids, composite grains, and intraclasts (Fig. 10). The cortices of ooids and most pisoids have radial crystal fabrics which may have formed in subaqueous hypersaline environments. Pisoids often contain micritic laminae which alternate with layers of radially fibrous crystals. Peloids in this facies are common and many are broken and slightly micritized pieces of *Ortonella*. Porosity is intergranular, intragranular, and solution-enhanced (vuggy) (Fig. 11). The main occluding cements are bladed and fibrous neomorphosed calcite, drusy calcite, prismatic calcite spar, and minor amounts of baroque dolomite and anhydrite. The coated-grain facies is the principal reservoir facies in island-shoal trends.

SALINA-SABKHA FACIES

This facies is comprised of nodular, bedded, and enterolithic anhydrite, and microcrystalline dolomite. Anydrite fabrics suggest that gypsum deposition occurred in subaqueous as well as supratidal environments. Porosity is poorly preserved in dolomites because of anhydrite replacement and cementation. Dolomites locally contain stromatolitic structures.

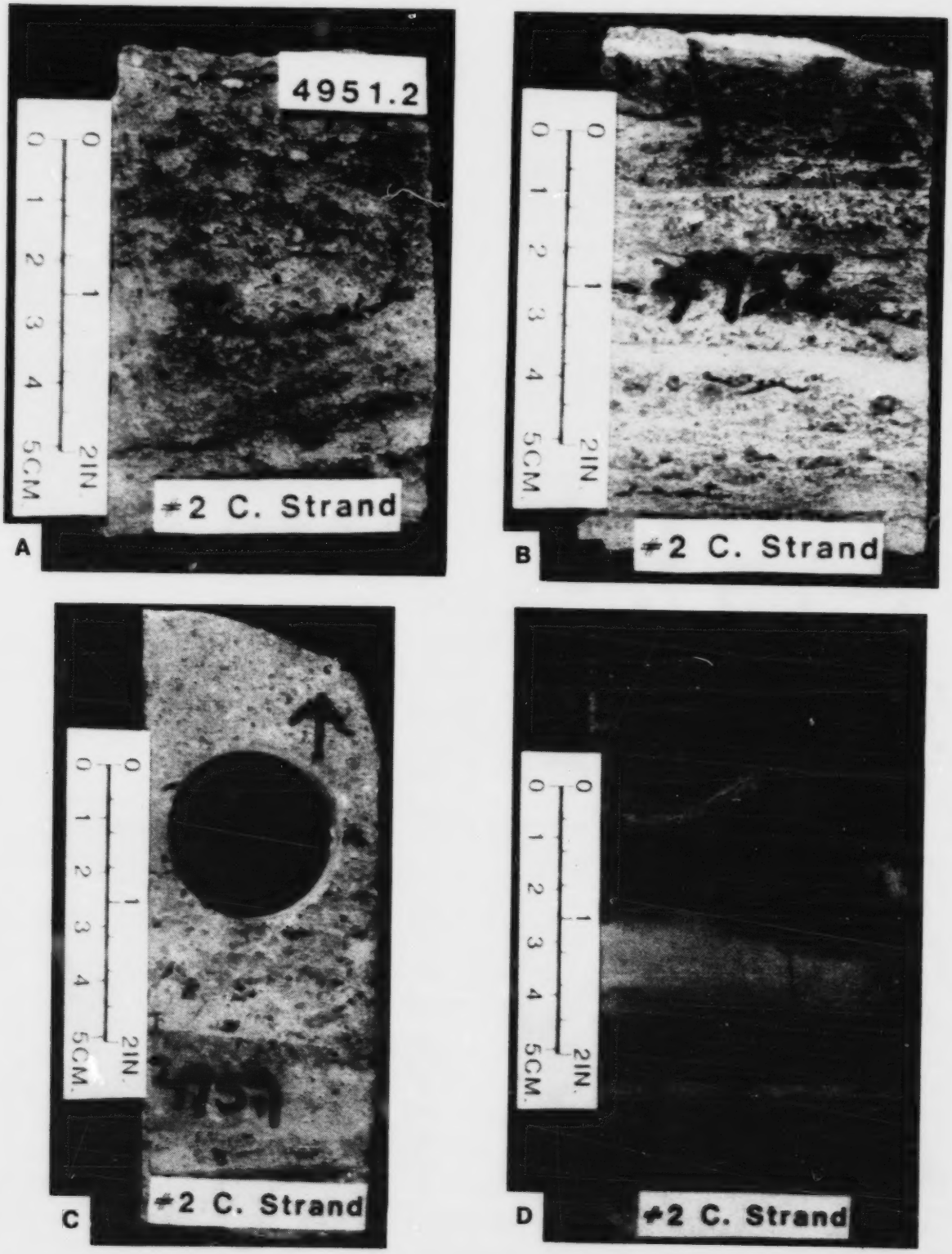


Fig. 5 Low-energy shoreline and lagoonal sediments typical of Sherwood fields near the carbonate-anhydrite facies change. (A) Peloidal and intraclastic wackestone of the reservoir facies. (B) Peloidal and intraclastic wackestone to packstones capped by thin carbonate mud drapes. (C) Peloidal and intraclastic wackestones with poorly developed pinpoint vuggy porosity. (D) Oil-stained, patterned carbonate with low-amplitude stylolites at top of sample. Samples from the Great Western #2 Strand, SW SE Sec. 30, T162N, R85W, Mouse River Park Field.

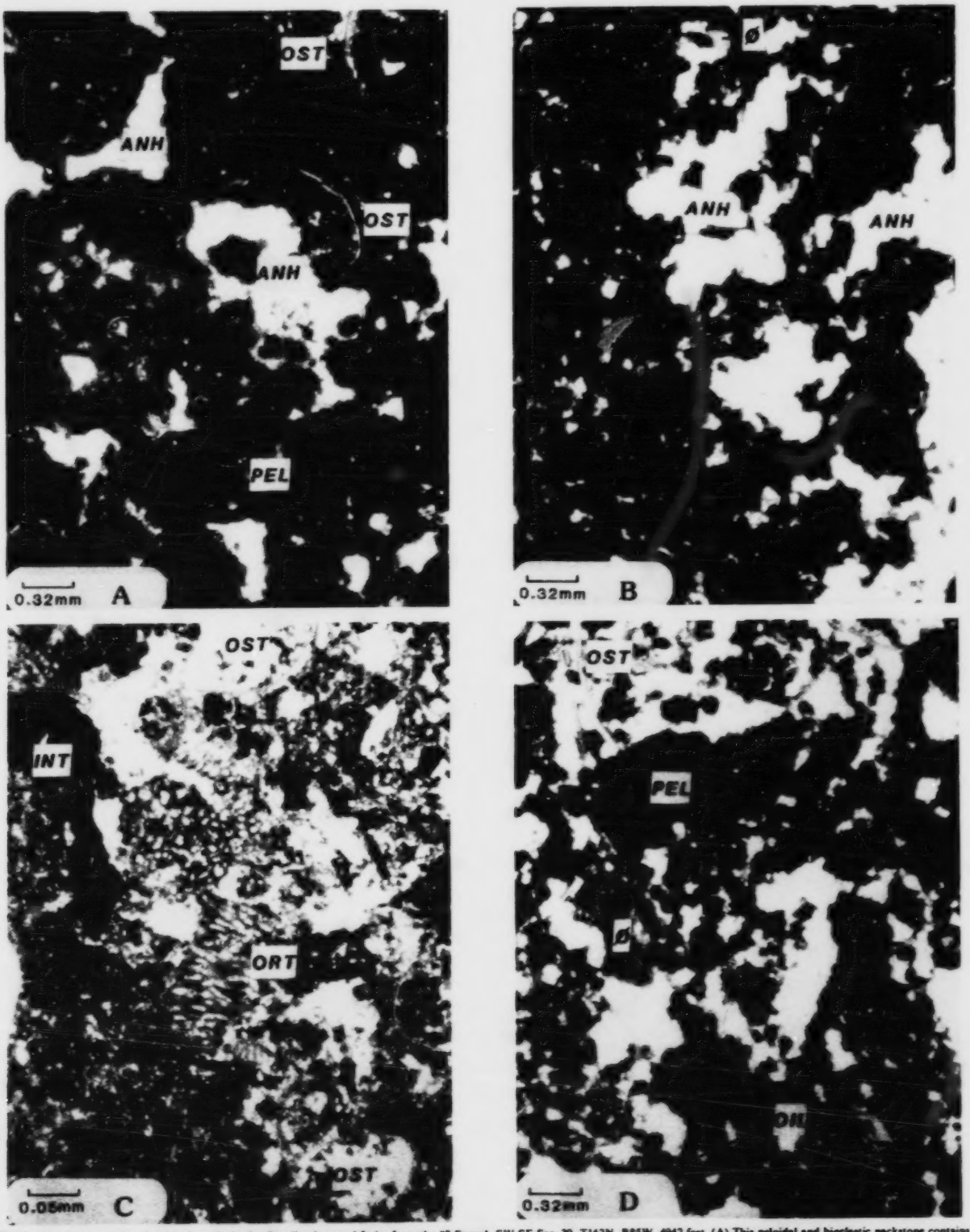


Fig. 6 Photomicrographs of reservoir rocks in the shoreline-lagoonal facies from the #2 Strand, SW SE Sec. 30, T162N, R85W, 4942 feet. (A) This peloidal and bioclastic packstone contains peloidal grains (PEL), ostracod bioclasts (OST), and anhydrite cement (ANH) which appears to be both pore occluding and replacive. (B) Anhydrite (ANH) replaced micrite and peloids and occluded most porosity in this packstone. (C) Shelter porosity, associated with ostracod carapaces (OST), is filled with blocky calcite. *Orionella* algae (ORT) with radiating microtubules and an intraclast (INT) are also shown. Porosity is almost completely occluded in this view. (D) Residual oil (OIL) coats small circular pores of *Orionella* microtubules (transverse sections). Solution (vuggy) porosity (O), partially occluded with blocky calcite and anhydrite cements, is ineffective because of its isolated nature. Micritized peloid (PEL) and ostracod carapaces (OST) are also shown.

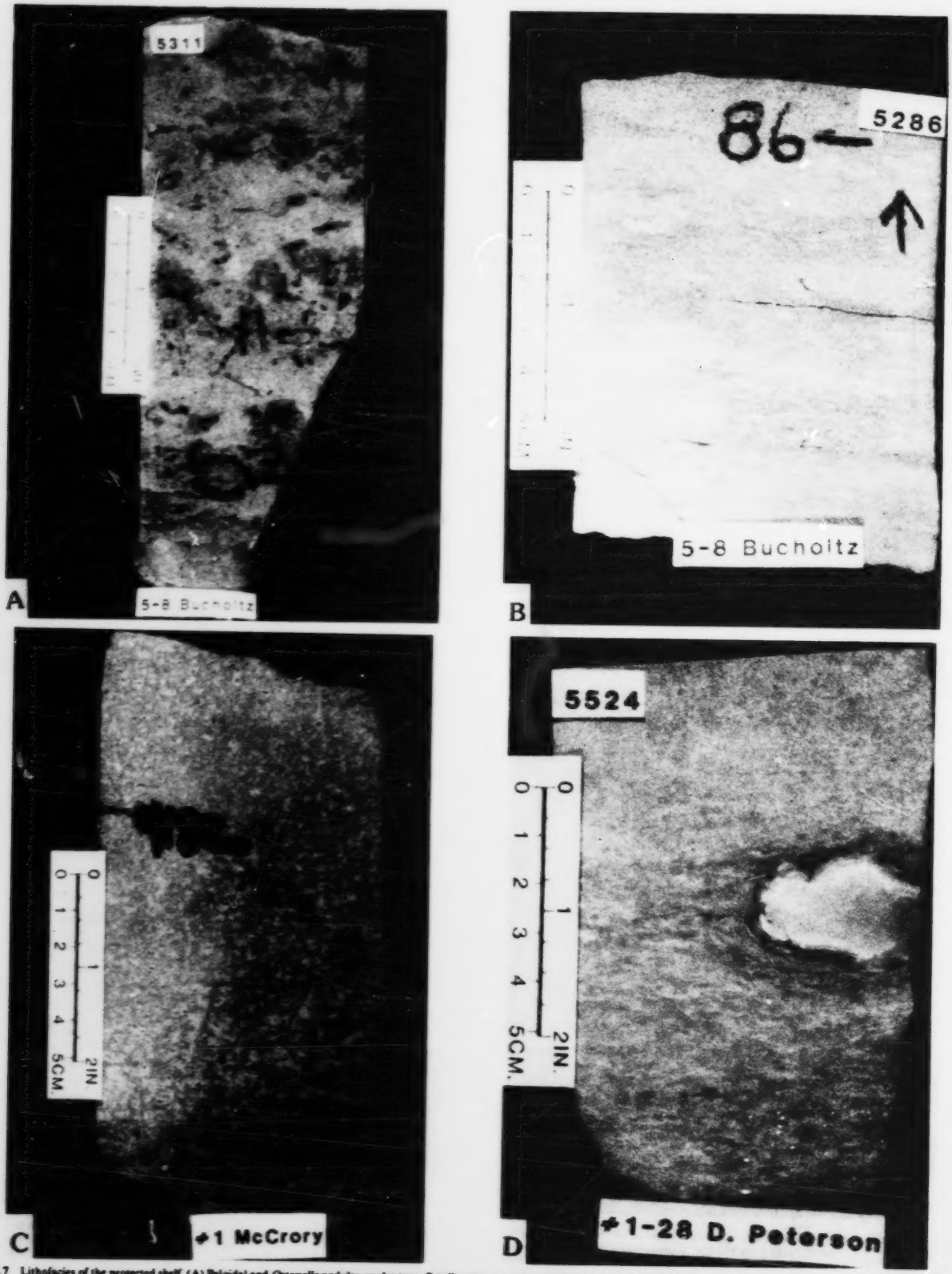


Fig. 7 Lithofacies of the protected shelf. (A) Peloidal and *Ortonella* nodular wackestone. Small vuggy pores are completely occluded with fibrous calcite, blocky calcite, and baroque dolomite. (B) Poorly developed *Chondrites* burrow structures near the base of this sample are commonly found in the protected shelf facies. Core samples A and B from the Kissinger 5-8 Bucholtz SE NW SEC. 8, T161N, R. 86W. These lithofacies are typical of protected shelf, lagoon, and low-energy "channel" environments. (C) Patterned beds (mottled appearance), produced by selective replacement of sulfates or carbonates by framboidal pyrite, occur locally in lagoonal environments. Sample from the Parker #1 McCrory, NW SE Sec. 3, T163N, R85W, Sherwood Field. (D) Massive-appearing dolomites of the Sherwood marker with a large replacive anhydrite nodule in the Petro-Lewis #1-28 Peterson, NE NE Sec. 28, T160N, R86W, Smith Field.

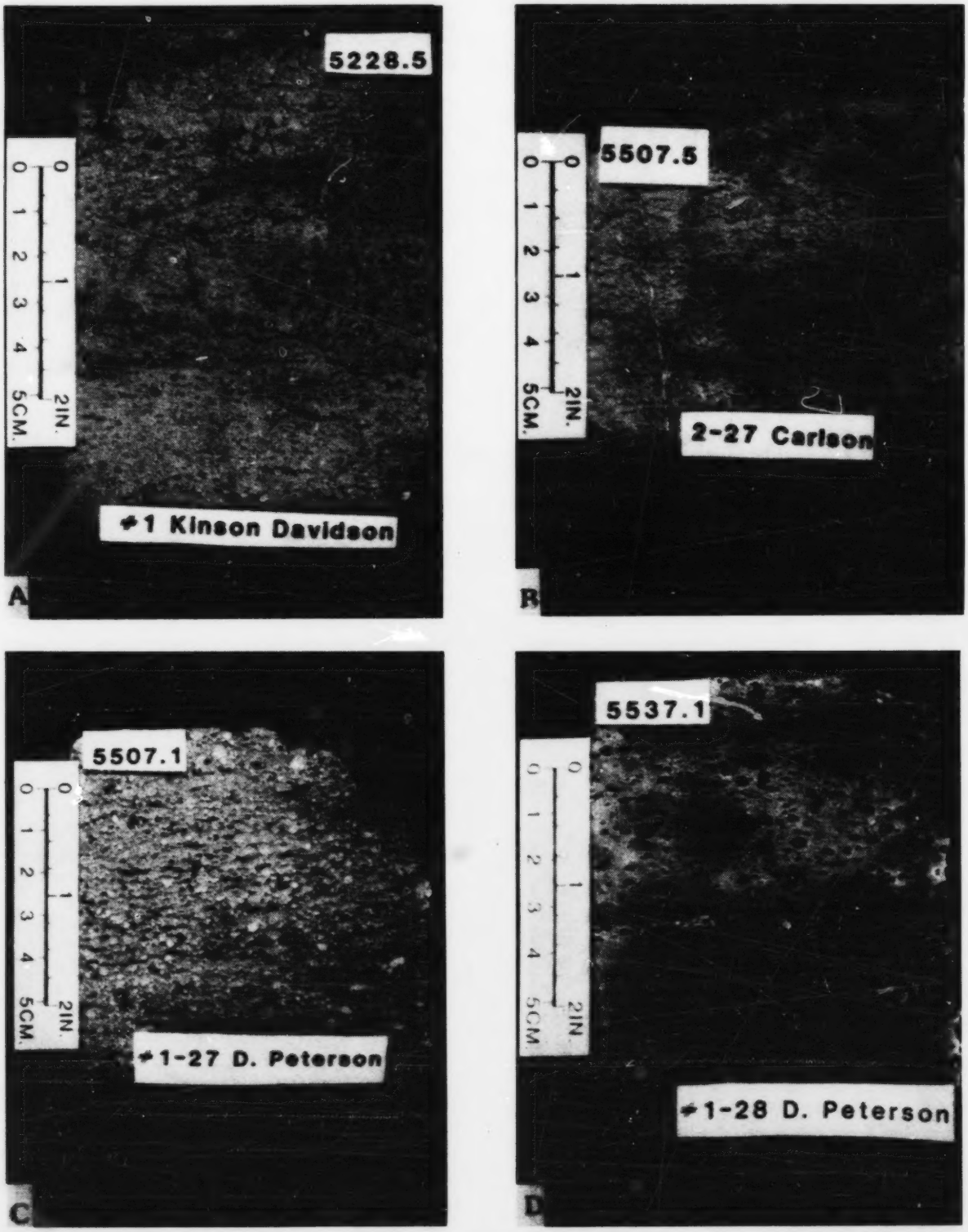


Fig. 8 Algal wackestones and packstones of the intertidal facies. (A) Fenestral fabric is poorly developed in this packstone from the Monsanto #1 Kinson Davidson, SE SE Sec. 7, T161N, R86W, in the McKinney Field. Note the vuggy pores which are aligned along some of the fenestrae. (B) Well developed fenestral fabric with oil-stained, solution-enhanced vuggy pores from the Smith Field, Petro-Lewis #2-27 Carlson, SE NW Sec. 27, T160N, R86W. (C) Fenestral porosity is solution-enlarged in this packstone sample from the Petro-Lewis #1-27 Peterson, NW NW Sec. 27, T16ON, R86W, Smith Field. Note the abundance of ooids and small peloids which were trapped along algal laminations. (D) Vuggy pores in an oil-stained wackestone from the #1-28 Peterson, NE NE Sec. 28, T160N, R86W, Smith Field.

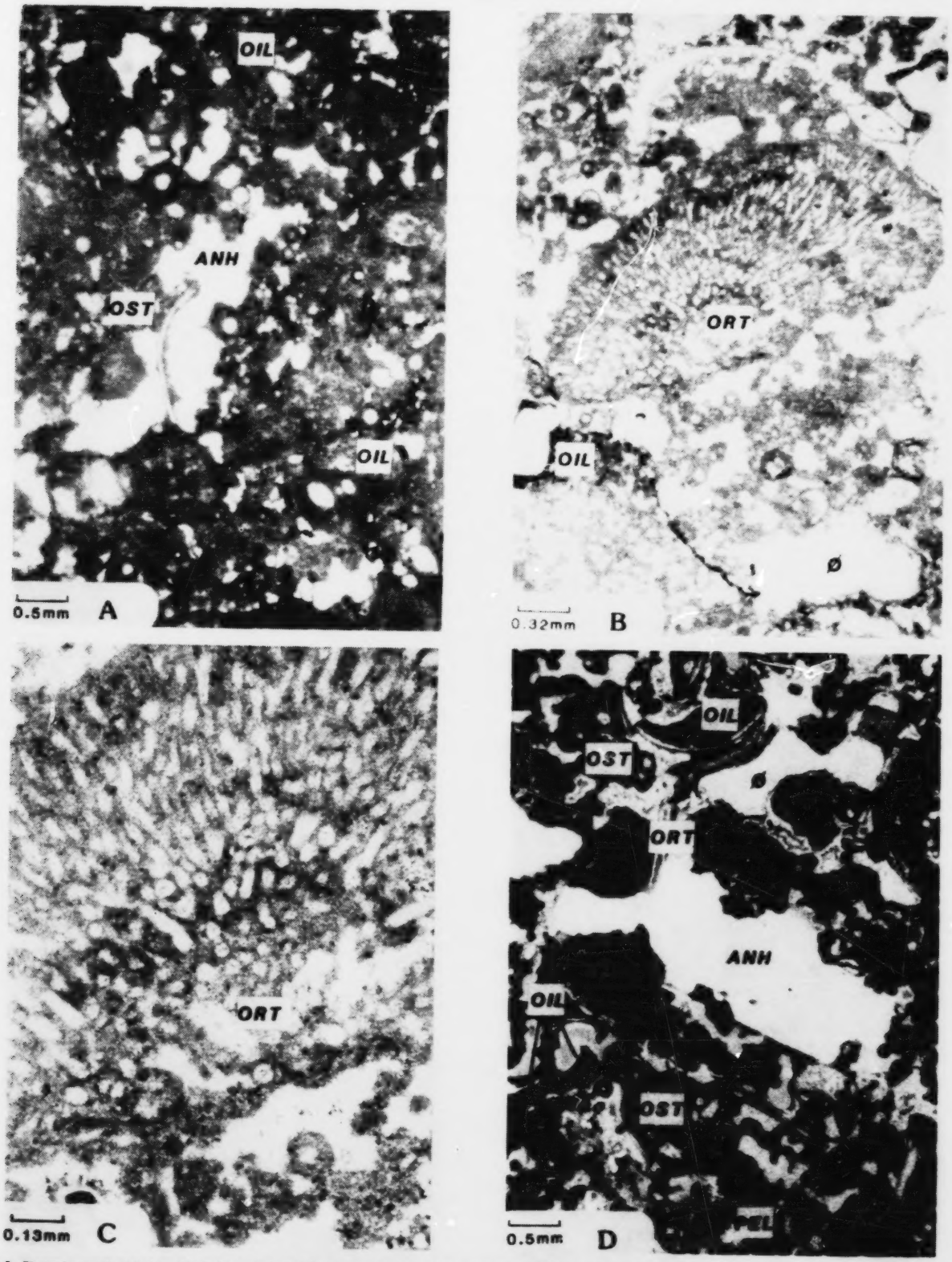


Fig. 9 Photomicrographs of the intertidal algal facies in the #1-B Ruach, Lot 3, Sec. 35, T164N, R85W, Sherwood Field. (A) Oil-stained pores (OIL) in this peloidal packstone are partially occluded with anhydrite (ANH). An ostracod carapace (OST) is unaffected by anhydrite. (B) An *Ortonella* colony is well preserved in this packstone. Residual oil (OIL) coats a pore at left. (C) Radiating microtubules of the *Ortonella* colony (ORT) are occluded with early marine, fibrous calcite cement. (D) The predominance of algae is readily seen in this sample. The very small, subrounded to rounded grains are pieces of *Ortonella* and dasycladacean algae. Some pieces are large enough that remnant *Ortonella* microtubules are preserved (ORT). Ostracods (OST) are randomly scattered throughout the sediments. Residual oil (OIL) coats many pores which are unoccluded by anhydrite (ANH). Vuggy porosity (O), as seen in this sample, accounts for the high oil recovery from the #1-B Ruach.

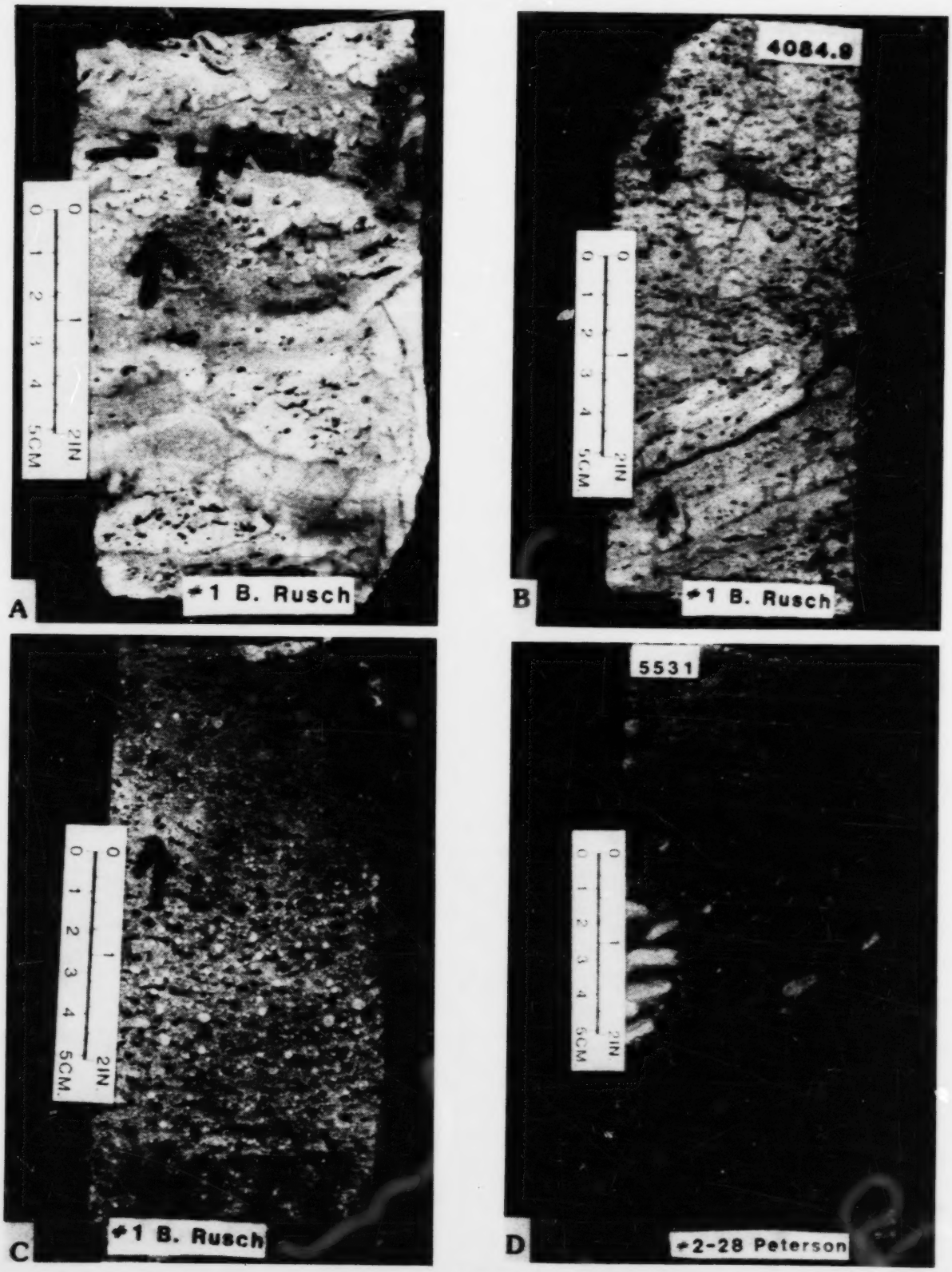


Fig. 10 Coated-grain facies of the intertidal-supratidal facies from the #1-B Rusch, Lot 3, Sec. 25, T164N, R85W, Sherwood Field. (A) Contorted calcrete crusts and inverse graded beds are part of this pisolitic packstone. These beds were probably deposited in intertidal-supratidal environments where subaerial exposure produced calichification. (B) Inferred teepee structures in intertidal sediments. (C) Well preserved fenestral and solution-enhanced vuggy porosity in an oolitic and peloidal packstone. Good porosity and permeability account for the high production rates in this well. (D) This packstone, from the #2-28 Peterson, SE NE Sec. 28, T160N, R86W, Smith Field, has ovoid pisoliths and unoccluded vuggy porosity. The upper part of the sample has algal laminated beds.

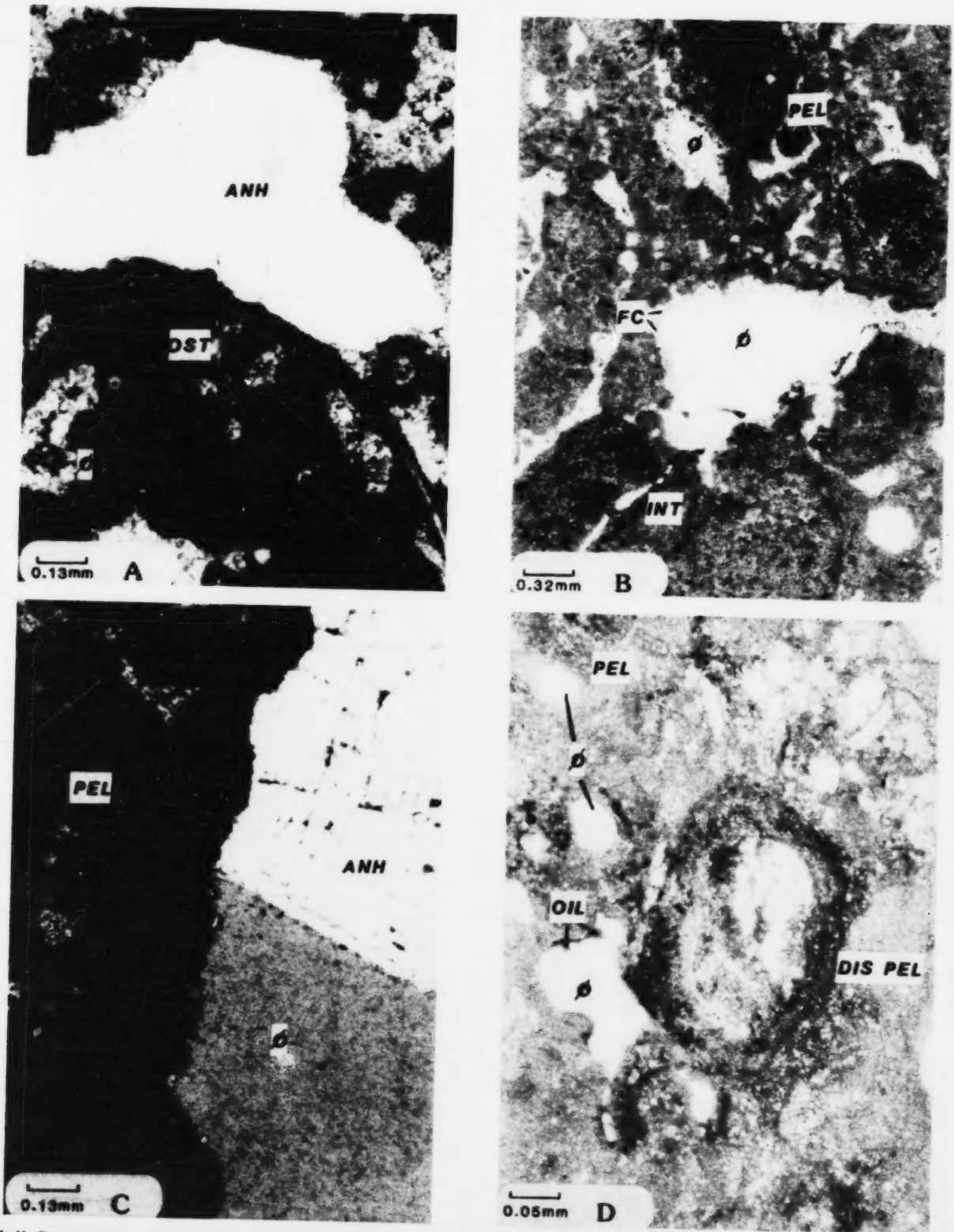


Fig. 11 Photomicrographs of the coated-grain facies from the #1-B Rusch, Lot 3, Sec. 25, T164N, R85W, 4066 and 4071 feet. (A) Anhydrite (ANH) occludes a vuggy pore in this packstone. An ostracod carapace (OST) is also shown. Unoccluded porosity (O) is present at bottom left. (B) Marine fibrous calcite cement (FC) rims large vuggy pores (fenestral pores?) in this peloidal packstone. Peloids (PEL) are slightly micritized and are interbedded with intraclasts (INT). (C) A highly magnified view of a vuggy pore shows partial occlusion by anhydrite (ANH). This pore is rimmed by fibrous calcite cement (FC). Small peloids (PEL) appear indistinguishable and massive because they are tightly packed. (D) A partially dissolved peloid (DIS PEL) is shown at center. Intraparticle porosity is occluded by blocky calcite cement. The small white specks are small dolomite crystals which have replaced micrite. Vuggy pores (O) contain dead oil (OIL). The interconnection of vuggy pores has produced an exceptional reservoir in these Sherwood beds.

Fig. 12 A wireline log cross-section from Elmore Field to the Sherwood Field showing the transition from anhydrite to carbonate and the development of the downdip island-shoal complex.

The abrupt updip facies change to anhydrite in shoreline fields provides a very effective permeability barrier for oil entrapment.

SHERWOOD DEPOSITIONAL MODEL

Sherwood beds in Renville County were deposited in island-shoal, lagoon-shoreline, and salina-sabkha environments. A wireline log cross-section (Fig. 12) from the Elmore Field to the Sherwood Field depicts this depositional setting. Subaqueous and supratidal anhydrites, which are part of the facies trap in the Elmore Field, change downdip to lagoonal mudstones and thin peloidal packstones. Sherwood beds are approximately 50 feet thick in the field (Fig. 13). Basinward in the Sherwood Field, beds thicken to more than 80 feet in island-shoal deposits (Fig. 13). The distribution of depositional facies and their thicknesses indicate that an increase in depositional slope controlled the position of the sabkha, lagoon, and island-shoal complex. A diagrammatic cross-section (Fig. 14) summarizes Sherwood depositional environments, oil-trapping mechanisms, and the transition from anhydrites to carbonates in this part of the basin.

Production has been greatly enhanced in the Sherwood Field because of pre-Triassic solutioning of the Prairie Salt. The removal of salt has produced significant structural closure (Fig. 15) which has probably doubled the height of the oil column.

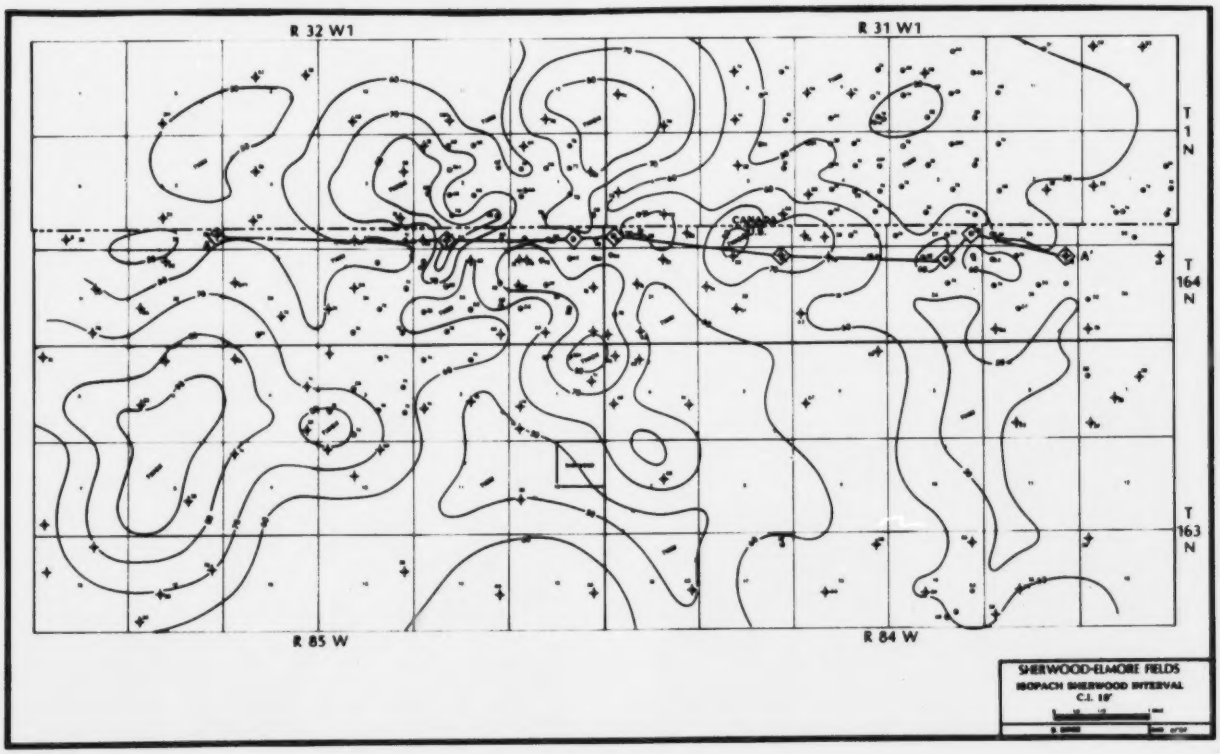


Fig. 13 An isopach map of the Sherwood beds in the Elmore and Sherwood Fields shows thickening of beds just west of the main anhydrite to carbonate facies change.

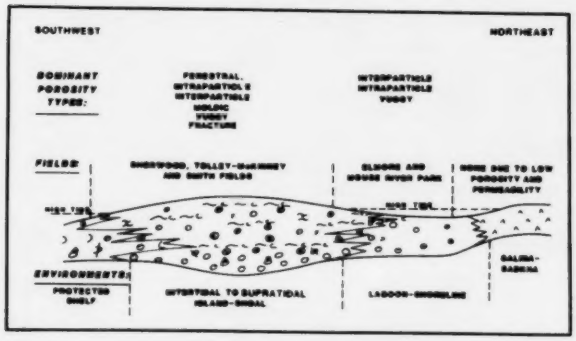


Fig. 14 Diagrammatic cross-section summarizes Sherwood depositional environments, porosity types, and the position of reservoirs relative to the anhydrite-to-carbonate facies change.

The relationship between depositional environments and changes in slope bathymetry in Sherwood beds is also manifest in the McKinney-Tolley Field (Figs. 16 and 17) and the Smith Field (Figs. 18 and 19) where Sherwood production is from island-shoal buildups. These reservoirs are draped across current anticlinal structures which plunge to the southwest.

A modern analogue to Sherwood depositional environments is unknown, but similarities exist between the Trucial Coast and ancient Mission Canyon coasts. Both developed on very gently sloping shelves and along embayed portions of shallow seas as a complex of islands, lagoons, and sabkhas.

A striking difference between the present Trucial Coast and the Sherwood depositional complex is the shape and composition of island-shoals. Near Abu Dhabi, islands form barriers elongate along depositional strike which are cut by tidal inlets. Island sediments are dominated by grains near beach barriers. These sediments grade into muds in the lagoons and in the middle and leeward portions of islands. Locally, the back parts of islands form well defined tombolos where supratidal environments persist (Fig. 20). Interisland areas are dominated by muds and skeletal sands on the lagoonal side of island-shoals, and by oolitic tidal deltas on the seaward side.

The shape of islands is partially dependent on waves originating from the "shamal" winds blowing from the northwest, off Qatar. These winds blow onshore approximately perpendicular to the barriers. Tidal currents with a range of approximately 1.5 m also modify the barrier islands by creating tidal inlets and tidal deltas (Shinn, 1975).

In comparison, Sherwood islands appear to be highly elongate along depositional dip, lack barrier beaches, are composed mostly of low-energy grains, and have poorly developed tombolos. Prevailing wind direction was from onshore (out of the northeast) following the pattern of trade winds which characterized the low latitudes of North America during the Carboniferous (Habicht, 1979). This restricted development of barrier islands and tombolos (Fig. 21).

Sherwood interisland areas are dominated by carbonate mudstones both on the seaward and lagoonal sides of island-shoals. Tidal energies and wave energies were very low, probably because of dampening across a broad and shallow depositional shelf.

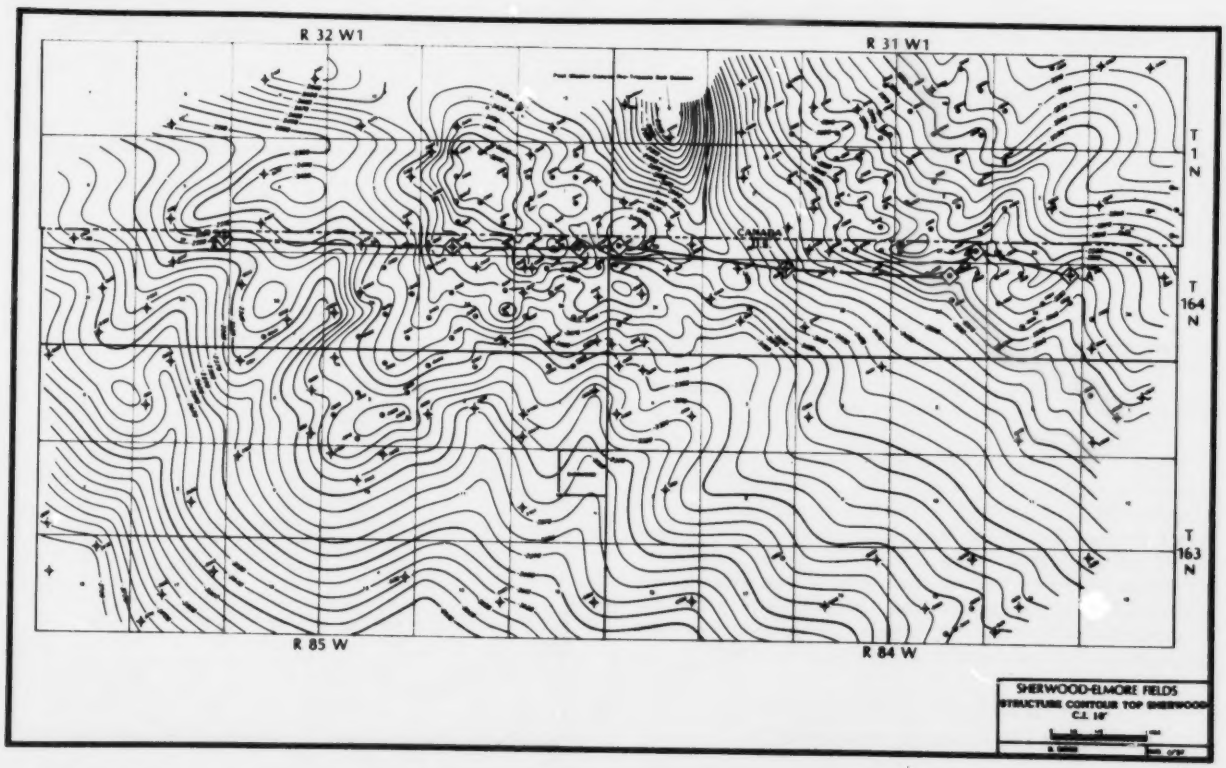


Fig. 15 Structure contour map on the top of the Sherwood. Pre-Triassic solutioning of the underlying Devonian Prairie Salt produced the pronounced low immediately northeast of the Sherwood Field.

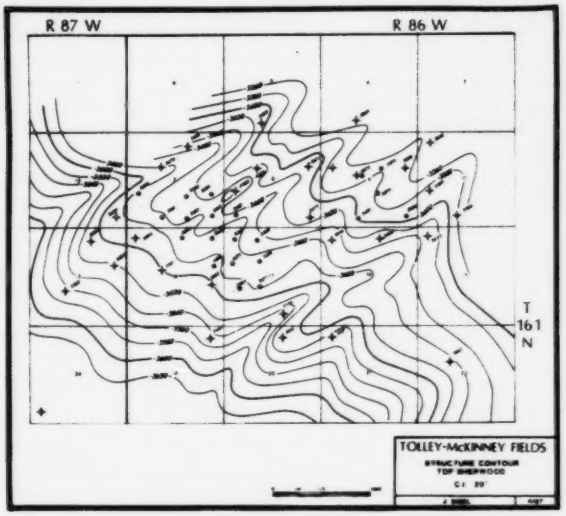


Fig. 16 Structure contour map on the top of the Sherwood in the McKinney-Tolley Fields.

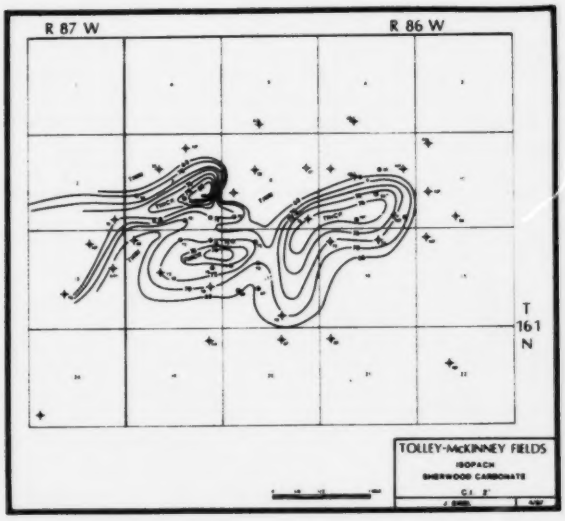


Fig. 17 Isopach map of the Sherwood carbonate in the McKinney-Tolley Fields. Bed thickening coincides with the development of an island-shoal buildup.

Details of the Sherwood depositional model are crucial to a successful exploration strategy. This is especially true in mapping the geometry and orientation of trap and reservoir facies. Sherwood shoreline-lagoonal trends are oriented northwest-southeast, along depositional strike. Island-shoal complexes are oriented northeast-southwest, reflecting basinward progradation of the system along paleostructural elements. Updip and lateral permeability seals for island-shoal reservoirs are lagoonal and low-energy channel muds (Fig. 14).

SHERWOOD EXPLORATION AND PRODUCTION HISTORY

Sherwood exploration in Renville County occurred in two stages. The first was initiated by the discovery of the Sherwood Field in February, 1958, continuing through the discovery of Mouse River Park in February, 1964. Exploration from 1964 through 1981 continued, but only sporadically. The second surge of exploration began in November, 1983, with the discovery of McKinney Field. The 1985 discovery of the Smith Field will promote exploration in this shallow play. Table 1 lists data on fields producing from Sherwood beds in the northern part of Renville County, their discovery dates, best wells, and cumulative production.

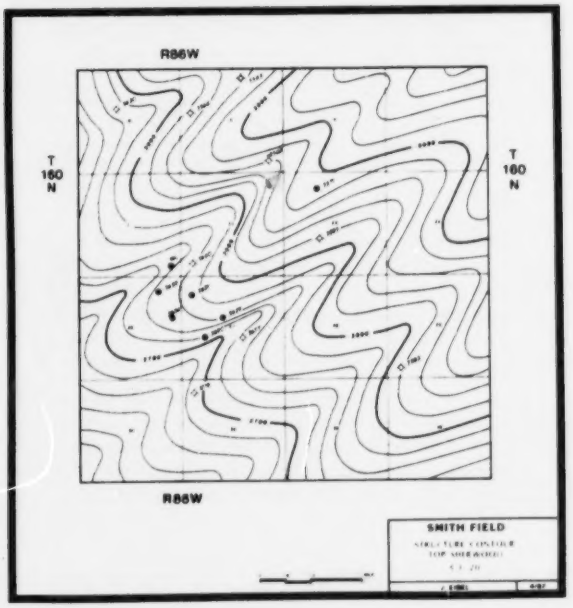


Fig. 18 Structure contour map on the top of the Sherwood in the Smith Field.

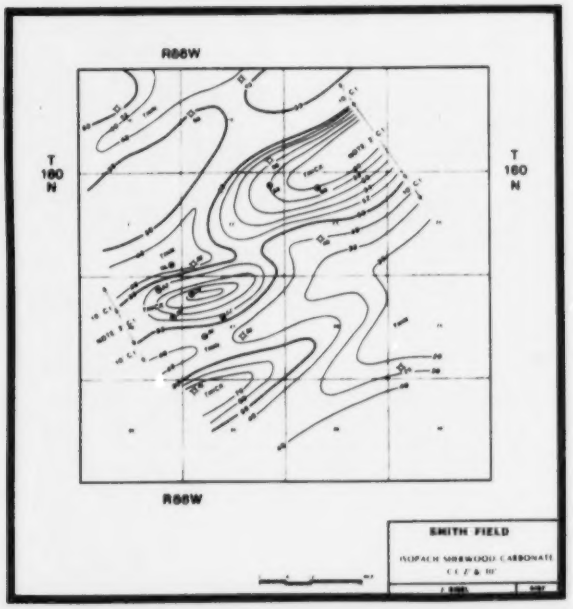


Fig. 19 Isopach map of the Sherwood carbonate in the Smith Field. Lateral and updip lagoon or low-energy "channel" traps are expressed as prominent isopach thins immediately adjacent to the field.

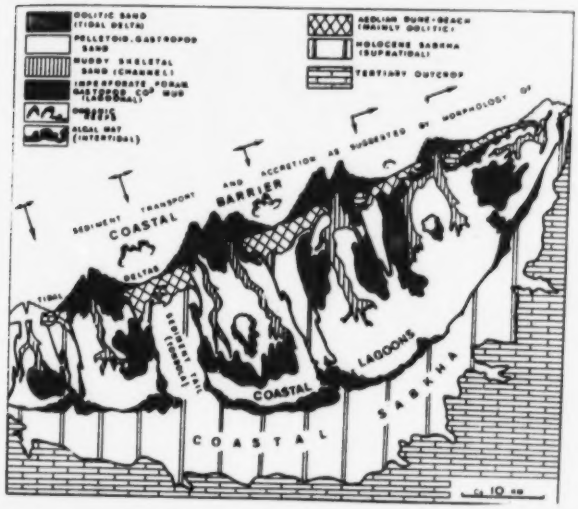


Fig. 20 Morphology of the Trucial Coast near Abu Dhabi. From Purser and Evans, 1973, p. 221.

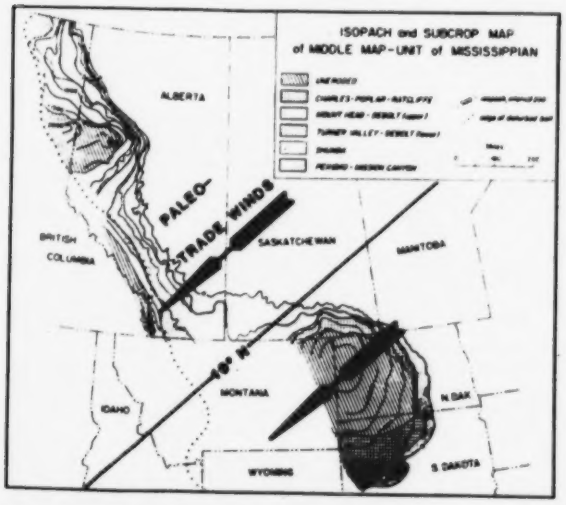


Fig. 21 Map showing the embayed position of the Williston Basin during Mission Canyon deposition (Procter and McCauley, 1968) and inferred paleolatitude and prevailing wind directions from Habicht, 1979.

The Sherwood Field has cumulative production exceeding 25 MMBO. In the U.S. portion of the field, The Chandler and Associates #1-B Rusch and the # 1 Rusch (Lots 1 and 3 of Sec. 25, T164N, R86W) have cumulative production of 1.9 MMBO and 1.6 MMBO respectively. Two wells just northwest of these in Saskatchewan have cumulative production of over 2 MMBO each (Placid Workman, 1-2-1-32 W1 and Placid Workman, 7-2-1-32 W1). Individual wells in the field (both Canadian and U.S.) have produced 600 MBO to over 1.5 MMBO. Average per well cumulative production for the Sherwood Field to date is in excess of 400 MBO.

In 1986, Chandler and Associates drilled two 40-acre offsets to the original Rusch wells. These wells, #2-B Rusch and the #2 Rusch (Lots 2 and 4 Sec. 25, T164N, R86W), apparently did not greatly affect reservoir pressures or production from the original wells (Fig. 22). Decline curves for the new wells are also included in Figure 22.

Within the recently discovered Smith Field, cumulative production data and decline curves (Fig. 23) from the Petro-Lewis #1-28 Peterson and #2-28 Peterson wells indicate that total Sherwood production should be high in these wells.

CONCLUSIONS

Sherwood beds in Renville County are part of the overall shallowing-upward, carbonate to anhydrite regression of the Mission Canyon Formation. Sherwood deposition along the northeast flank of the basin occurred in sabkha, shoreline-lagoon, and low-energy island-shoal environments. The depositional limits of these environments were controlled by

Table 1. Sherwood production

Field: Tolley
Spacing: 80 acres
Discovery Date: 1/25/63
Discovery Well: Hunt #1 State Hembre, NENW 16, 161N, 86W
I.P.: T.A.
Oil Gravity: 41.3 degrees API
Depth: 5300 ft.
Bottom Hole SIP: 2338 PSI (DST)
Producing Formation: Sherwood
Best Well: Hunt Industries, C. Knutson #1, SESW 9, 161N, 86W, 436,473 BO/302,755 BW
Total Field Production: 871,882 BO/496,114 BW; 8 wells; 9/30/86
Depositional Environment: Island-Shoal
Trap: Impermeable lagoonal facies

Field: Elmore (U S portion)
Spacing: 80 acres or 2/80 acres
Discovery Date: 6/8/61
Discovery Well: Cardinal Aubrey Harkness #1, SWSE 28, 164N, 84W
I.P.: 162 BOPD, 30% water
Oil Gravity: 32 degrees API
Depth: 4000 ft.
Bottom Hole SIP: 1772 PSI
Producing Formation: Sherwood and Midale (Rival)
Best Well: Ranger Oil Co., Harkness #4-27, Lot 4 of 27, 164N, 84W 337,759 BO/215,987 BW
Total Field Production: 1,873,310 BO/766,141 BW; 20 wells; 9/30/86
Depositional Environment: Shoreline-lagoon
Trap: Facies change to anhydrite

Field: Sherwood (U S portion)
Spacing: 80 acres or 2/80 acres
Discovery Date: 2/6/58
Discovery Well: Gulf Oil #1 W. Rusch, SENW 3, 163N, 85W
I.P.: 245 BOPD, 10 BW
Oil Gravity: 29.4 degrees API
Depth: 4300 ft.
Bottom Hole SIP: 1765 PSI
Producing Formation: Sherwood
Best Well: Chandler and Associates, #1B. Rusch, Lot 3 of 25, 164N, 85W 1,927,247 BO/172,355 BW
Total Field Production: 15,263,624 BO/8,245,432 BW; 41 wells; 9/30/86
Depositional Environment: Island-shoal
Trap: Impermeable lagoonal facies

Field: Mouse River Park
Spacing: 80 acres
Discovery Date: 2/24/64
Discovery Well: Arex Corp. #1 Hellebust SESW 19, 162N, 85W
I.P.: 102 BO, 83 BWPD
Oil Gravity: 28 degrees API @ 60 degrees
Depth: 4900 ft
Bottom Hole SIP: 2158 PSI (DST)
Producing Formation: Sherwood
Best Well: Kaiser-Francis Oil, #1 Hess, SWSE 24, 162N, 86W 178,711 BO/8144 BW
Total Field Production: 2,997,115 BO/364,712 BW; 42 wells; 9/30/86
Depositional Environment: Shoreline-lagoon
Trap: Facies change to anhydrite

Field: McKinney
Spacing: 40 acres or 2/80 acres
Discovery Date: 1/7/84
Discovery Well: Monsanto Oil #1 Kinson-Davidson, SESE 7, 161N, 86W
I.P.: 120 BOPD
Gravity: 28 degrees API @ 60 degrees
Depth: 5350 ft
Bottom Hole SIP: 2340 PSI (DST)
Producing Formation: Sherwood
Best Well: Tenneco Oil Co., #1-17 Tenneco, NWNW 17, 161N, 86W 141,178 BO/61,144 BW
Total Field Production: 758,870 BO/850,560 BW; 17 wells; 9/30/86
Depositional Environment: Island-shoal
Trap: Impermeable lagoonal facies

Field: Smith
Spacing: 80 acres
Discovery Date: 11/25/85
Discovery Well: Petro-Lewis Corp. #1-28 Peterson, NENE 28, 160N, 86W
NENE 28, 160N, 86W
I.P.: 682 BOPD
Gravity: 27 degrees API @ 60 degrees
Depth: 5540 ft
Bottom Hole SIP: 2460 PSI (DST)
Producing Formation: Sherwood and Bluell
Best Well: Petro-Lewis 2-28 Peterson, SENE 28, 160N, 86W, 148,790 BO/7680 BW
Total Field Production: 314,856 BO/22,976 BW;
Depositional Environment: Island-shoal
Trap: Impermeable lagoonal facies

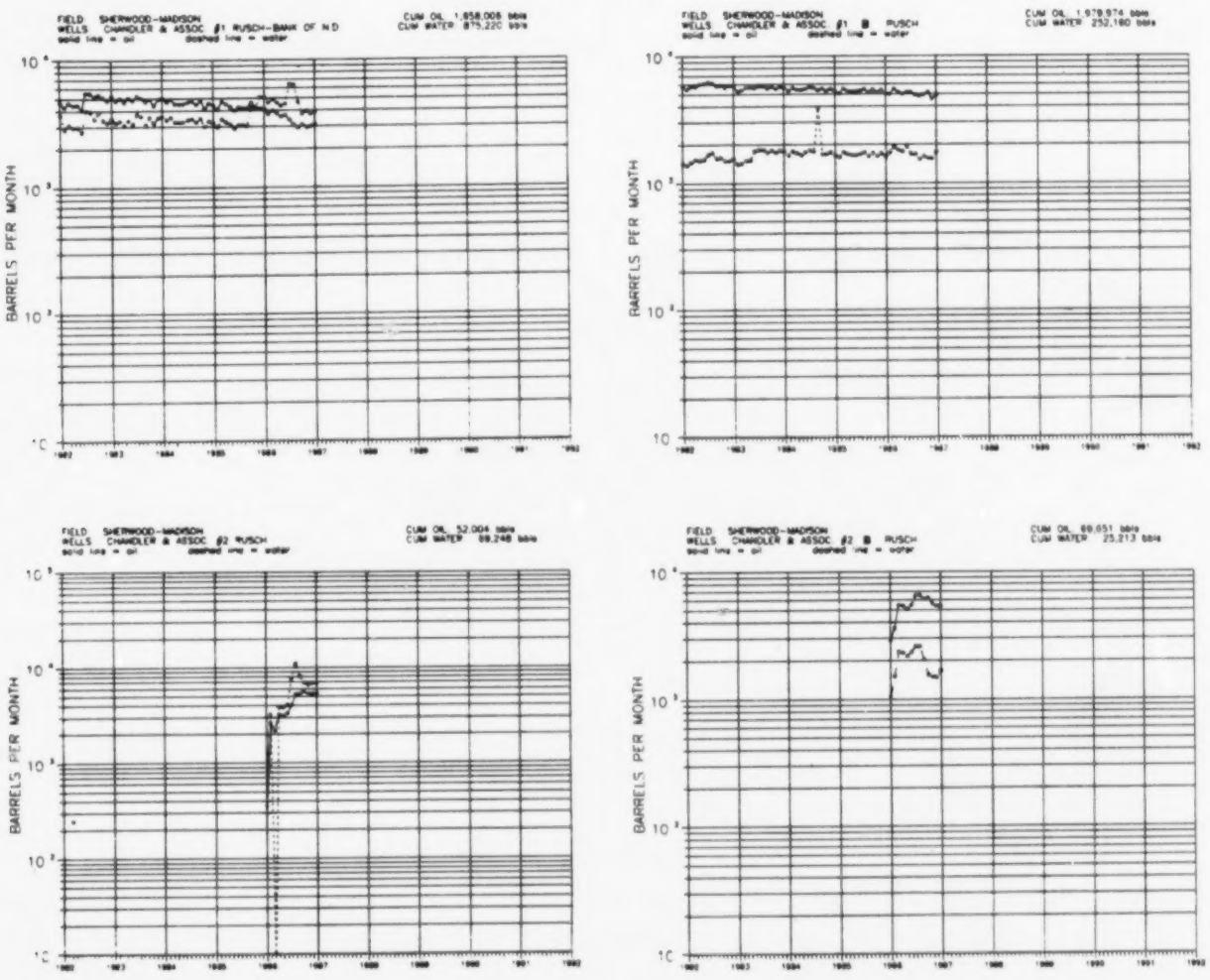


Fig. 22 Decline curves for the Chandler and Associates Rusch wells, Sherwood Field.

paleobathymetry which was a reflection of paleostructure. Porous and permeable carbonate reservoirs developed downdip and slightly basinward of anhydrite facies, at or near breaks in the depositional slope.

A modern analogue to Sherwood deposition exists in the Abu Dhabi areas of the Trucial Coast. Similarities and differences between the modern and ancient models have defined a useful approach to finding Sherwood exploration targets. Detailed regional and local stratigraphic analyses offer new insights for the discovery of significant reserves in Sherwood beds.

ACKNOWLEDGEMENTS

Special thanks are given to individuals who helped in the preparation of this manuscript. Thomas Hendricks, SRG Inc., photographed core samples; Linda Flis provided technical services; Jeff Corbin and Rita Mitton drafted figures; and John Grube edited the manuscript.

REFERENCES CITED

Beach, D., and Schumacher, A., 1982, Stanley Field, North Dakota: a new model for a new exploration play. In: Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication No. 6, p. 234-243.

Cook, J. D., and Bally, A. W., eds., 1975, Stratigraphic atlas of North America, prepared by the exploration staff of Shell Oil Company, Houston, Texas: Princeton University Press, Princeton, New Jersey, 272 p.

Dixon, J., 1976, Patterned carbonate - diagenetic feature: Canadian Petroleum Geology Bulletin, v. 24, p. 450-456.

Eddie, R. W., 1958, Mississippian sedimentation and oil fields in southeastern Saskatchewan: AAPG Bull., v. 42, p. 94-126.

Eisel, J. D., and Hendricks, M. L., 1986, South Coteau Field: integration of geology, petrophysics, and engineering yields Mission Canyon Oil: Wyoming Geological Association Symposium: Rocky Mountain Oil and Gas Fields, p. 45-59.

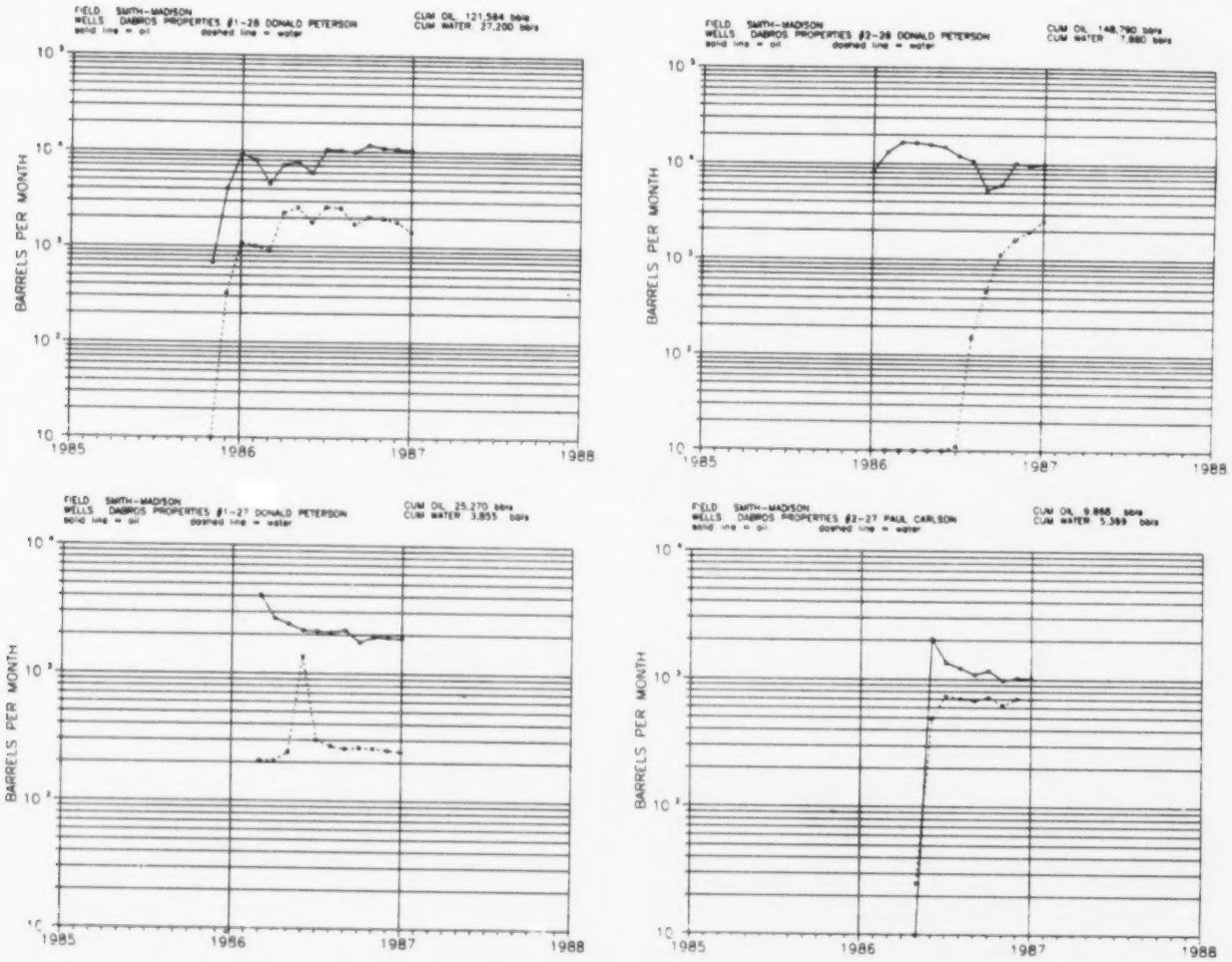


Fig. 23 Decline curves for wells from the Smith Field, Renville County, North Dakota.

Elliott, T. L., 1982, Carbonate facies, depositional cycles, and the development of secondary porosity during burial diagenesis: Mission Canyon Formation, Haas Field, North Dakota. In: Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication No. 6, p. 131-151.

Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C.G., 1982, Geological development, origin, and energy and mineral resources of Williston Basin, North Dakota: AAPG Bull., v. 66, p. 989-1020.

Habicht, J. K. A., 1979, Paleoclimate, paleomagnetism, and continental drift: AAPG Studies in Geology, No. 9, 31 p. and 11 foldouts.

Harris, S. H., Land, C. B., and McKeever, J. H., 1966, Relation of Mission Canyon stratigraphy to oil production in north-central North Dakota: AAPG Bull., v. 50, p. 2269-2276.

Lindsay, R. E., 1985, Rival, North and South Black Slough, Foothills and Lignite oil fields: their depositional facies, diagenesis and reservoir character, Burke County, North Dakota. In: Rocky Mountain Carbonate Reservoirs - A Core Workshop, SEPM Core Workshop #7, p. 217-263.

Malek-Aslani, M., 1971, Depositional environment of Mission Canyon (Mississippian) oil fields in north-central North Dakota (abs.): AAPG Bull., v. 55, p. 351.

Procter, R. M., and McCauley, G., 1968, Mississippian of Western Canada and Williston Basin: AAPG Bull., v. 52, p. 1956-1968.

Purser, B. H., and Evans, G., 1973, Regional sedimentation along the Trucial Coast, SE Persian Gulf. In: B. H. Purser (ed.), The Persian Gulf: Springer Verlag, New York, p. 211-231.

Shinn, E. A., 1973, Carbonate coastal accretion in an area of longshore transport, NE Qatar, Persian Gulf. In: B. H. Purser (ed.), The Persian Gulf: Springer Verlag, New York, p.179-191.

Voldseth, N. E., 1986, Flaxton Field, Burke County, North Dakota: Wyoming Geological Association Symposium: Rocky Mountain Oil and Gas Fields, p. 21-43.

KNUTSON FIELD AND ITS RELATIONSHIP TO THE MISSION CANYON OIL PLAY, SOUTH-CENTRAL WILLISTON BASIN

ROBERT W. BOGLE[1] AND WILLIAM B. HANSEN[2]

ABSTRACT

Knutson Field lies on the Billings-Golden Valley County line adjacent to the western border of Theodore Roosevelt National Park. The field was discovered by Diamond Shamrock Exploration Company in 1983 with the completion of a 9325' Mission Canyon well. As of January 1, 1987, sixteen wells were producing 2583 BOPD and 7948 BWPD, and had made 1,993,073 BO and 4,374,170 BW. The field should ultimately recover in excess of 4 MMBO.

Three factors affect accumulation of oil in the two pools of Knutson field, as well as in two Rider field wells to the south: 1) a north plunging anticlinal nose; 2) a NE-SW-trending pinchout of the Mission Canyon dolomitic reservoir; and 3) mobile Mission Canyon ground water flowing from the southwest. Furthermore, these factors to varying degrees affect all Mission Canyon oil fields of the south-central Williston Basin.

Due to the high cost of drilling and operating wells in this area, future exploration for similar reservoirs must take into account all three of the above factors.

INTRODUCTION

Knutson Field is located in the southwestern portion of the Williston Basin (Fig. 1), six miles northwest of Medora, North Dakota. The field occurs along the Billings-Golden Valley county lines in Townships 140-141 North, and Ranges 102-103 West and lies adjacent to the western boundary of Theodore Roosevelt National Park (south unit).

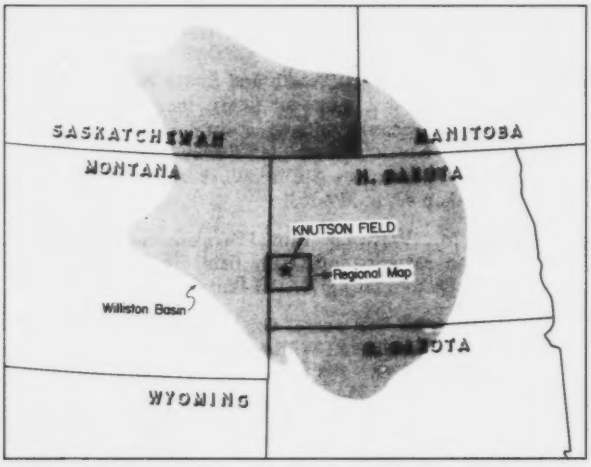


Fig. 1. Williston Basin index map showing outline of regional study area and location of Knutson field.

[1] *Diamond Shamrock Exploration Company*
370 17th Street
Suite 2900
Denver, Colorado 80202

[2] *Division of Mineral Resources*
*U.S. Bureau of Land Management **
P.O. Box 36800
Billings, Montana 59107

Virtually all the production in the field, as well as in two of three older Rider field wells to the south, comes from a Mississippian Mission Canyon interval, referred to in this paper as the "Knutson" porosity zone (Fig 2). The "Knutson" underlies an 80-100' anhydrite section within the Mission Canyon, known locally as the "Nesson" anhydrite.

FIELD DISCOVERY AND DEVELOPMENT

Knutson field was opened October 9, 1983 with the completion of the Diamond Shamrock Exploration Company 21-6 Ramona Federal (Fig. 3), in the NENW 1/4 of section 6, T14ON, R102W, Billings county, North Dakota. From August

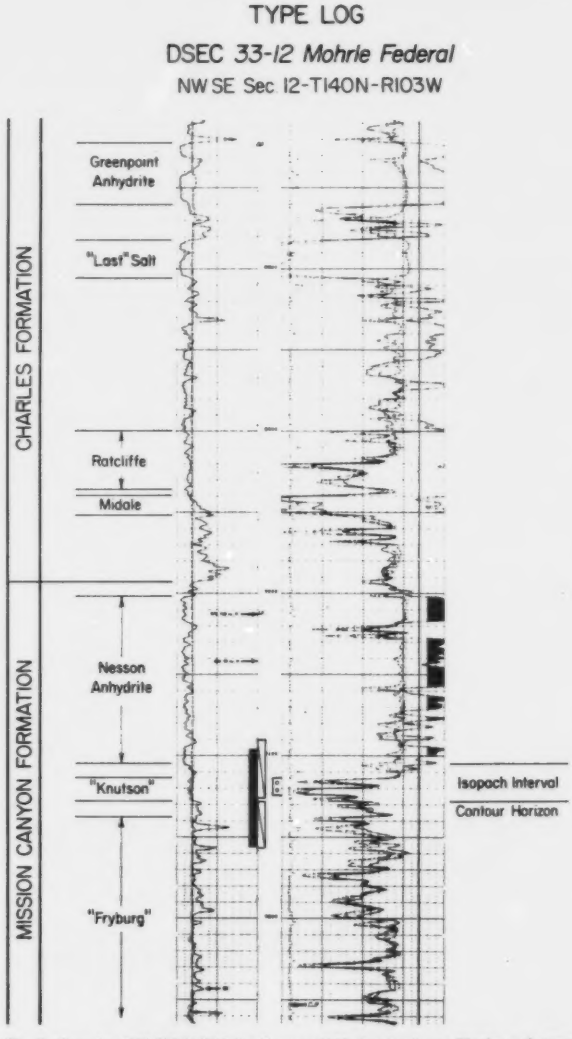


Fig. 2 Type log (GR-FDC-CNL) for Knutson field showing lower Charles and upper Mission Canyon Formations. "Contour Horizon" indicates marker on which structure contour maps (Figs. 4 and 5) were drawn.

* *The contents of this paper do not necessarily reflect the views and policies of the U.S. Bureau of Land Management, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.*

Fig. 3 Photograph, looking east, of the Knutson discovery well, Diamond Shamrock Exploration Company's 21-6 Ramona Federal. Shown drilling in September, 1983 in the "Badlands" of North Dakota.

1983 through February 1986 the field was delineated by 27 wells, including 24 drilled by Diamond Shamrock. Of these, 16 became Diamond Shamrock Mission Canyon producers (Table 1), 8 were Diamond Shamrock failures (including two cased and production tested), and 3 were drilled and abandoned by other operators.

Table 1. Production data for Knutson Field, chronological by completion date.

PRODUCTION SUMMARY
(As of 1-1-87)

WELL NAME	LOCATION	COMPLETION DATE	IP (BOPD)	IP (BWPD)	CURRENT RATE (BOPD)	CURRENT RATE (BWPD)	CUM OIL (BO)	CUM WTR (BW)
RAMONA FED 21-6	NENW 6-140-102	10/08/83	151	92	68	123	133989	277482
KEY FED 33-33	NWSE 33-141-102	12/26/83	78	28	93	342	86043	243949
DSC STATE 13-34	NWSW 34-141-102	02/01/84	60	18	77	323	95036	283947
HARRIS FED 31-33	NWNE 33-141-102	08/31/84	42	364	31	327	35139	280103
LODEMA FEE 41-1	NENE 1-140-103	10/14/84	74	708	41	469	42396	347203
COREY FED 12-5	SWNW 5-140-102	04/19/85	778	805	139	457	223016	342236
MOHRLE FED 33-12	NWSE 12-140-103	05/09/85	877	12	770	264	389245	75925
NORMA FED 31-6	NWNE 6-140-102	06/05/85	37	508	59	274	38618	216253
HUNT FED 21-13	NENW 13-140-103	09/03/85	645	672	196	2050	236194	841540
MOHRLE FED 22-12	SENW 12-140-103	09/03/85	419	633	67	764	83127	388221
NORMA FEE 43-6	SENE 6-140-102	09/14/85	155	527	114	380	65838	215374
MOHRLE FED 13-12	NWSW 12-140-103	09/23/85	499	423	164	573	120729	225017
DSC STATE 11-34	NWNW 34-141-102	09/23/85	38	250	49	234	19107	113356
MOHRLE FED 42-12	SENE 12-140-103	11/12/85	643	427	98	725	85699	280150
RAMONA FEE 23-6	SENW 6-140-102	11/21/85	730	505	414	445	241721	189292
RAMONA FEE 24-6	NESW 6-140-102	01/27/86	321	160	203	198	97176	54122
	TOTALS		5547	6132	2583	7948	1993073	4374170

The prospect was originally conceived as a Medora field look-alike with objectives in the Pennsylvanian Tyler and the Mississippian "Fryburg" (Fig. 2). Existing well control in Sections 10 and 13, T14ON, R103W and Sections 20, 29 and 30, T141N, R102W suggested a structural nose off the regional NW-SE strike. Seismic data showed subtle structural closure and accompanying isochron thins in Section 6, T14ON, R102W, and Section 33, T141N, R102W. In other words, the prospect appeared technically weak. As is often the case, drilling was finally prompted by the imminent expiration of a key lease.

The 21-6 Ramona well was spudded on August 14, 1983, and on September 5, recovered 845' gas, oil and mud emulsion, 2112' highly gas-cut oil, and 2426' formation water in the pipe, and 1200cc oil, 1800 cc water and 0.5 cubic foot of gas in the sample chamber from the Mission Canyon drillstem test (DST) interval 9132'-9174.' Original reservoir pressure was 4208 psi. The well was later completed pumping 151 barrels of 35 degree API oil per day (BOPD) and 92 barrels of water per day (BWPD) with gas too small to measure from perforations in the "Knutson" zone. Significantly, the pay lay stratigraphically 10 to 15 feet above the porous horizon productive at Medora field.

Testing of deeper objectives in the area has been limited. One Knutson field well was drilled through the Ordovician Red River Formation but was plugged back to the Mission Canyon after having failed to establish deeper pay. The one-well Wannagan field in section 30, T141N, R102W, is the area's only deeper-pay success so far, having recovered over 200,000 BO from the Red River with very little water. There have been only seven tests within seven miles of the field penetrating rocks below Mission Canyon, and all have been north of the field.

Other objectives have failed to be productive. Sands in the Tyler Formation are sparse and nitrogen-bearing. Mississippian Ratcliffe and Midale zones of the Charles Formation are tight and/or wet. The "First Fryburg" (Fig. 2 at 9134' measured depth), which is productive in Medora, Square Butte, West Fryburg and Bullsnake fields (Fig. 4) and in the southern Billings Nose complex, has minimal production in Knutson field. One Rider field well recovered 4000 BO and 72,000 BW from the "First Fryburg" before being plugged.

DRILLING AND COMPLETION PRACTICES

Following is a listing and summary of drilling and completion practices employed in Knutson field:

The first five wells were drilled with saturated brine mud. The remaining 19 Diamond Shamrock holes used an invert system, emulsified diesel (70%) and salt-saturated brine (30%), to decrease rugosity through the salt formations. This change required a switch from laterolog to induction-type resistivity tools, eliminated the R_{xo} tool, rendered fluid saturations from core useless, and lessened significance of drilling sample shows.

Drillstem testing was the key evaluative procedure, with empirical minimums for casing a well being 10% oil in sample chamber and 1000 feet of total fluid recovered from the drillpipe. Log analysis was of lesser value because of apparent variability of formation water resistivity (R_w).

The "Knuston" zone was generally perforated over a four-to-eleven foot interval, with two exceptions. Several of the early wells were perforated from the base of the "Knutson" up to the base of Nesson anhydrite on the theory that natural fractures in this overlying "tight" limestone section could increase deliverability. A second group of wells were additionally perforated in "Fryburg" zones when one well, the 12-5 Corey Federal, flowed oil and water for several days following acidization of the "First Fryburg."

Completion of a typical well followed these steps: 1) swab test; 2) Stressfrac (a patented technique involving stimulation with a downhole gas generator); 3) swab; 4) acidize; 5) swab; and 6) put on pump. All wells were completed pumping. Depending on results of the final swab testing, the pump was selected from three types: rod, hydraulic or electric submersible.

PRODUCTION

The sixteen wells were producing slightly under 2600 BOPD (Table 1) as of January 1, 1987. API gravity averages 35 degrees for the northern wells and 37 degrees for the southern wells. The field is estimated to recover in excess of 4 MMBO.

The field produces 2200 BTU gas at a ratio of 120 standard cubic feet per barrel of oil. A gas processing plant strips out 3000 gallons per day of natural gas liquids, removes minor amounts of hydrogen sulfide, and makes the remaining dry gas available for lease use. No dry gas is sold.

Eight thousand barrels per day of produced water are currently injected into Cretaceous Dakota sandstone through three disposal wells. A fourth hole is presently awaiting conversion to a Permian Minnelusa disposal well.

CORE AND LOG ANALYSIS

In the field, the "Knutson" zone consists of three discrete porous horizons with 12 to 14 feet of aggregate thickness. Log porosity ranges from 0 to 26% and core permeability from less than 0.01 millidarcy to 64 millidarcies. The minimum effective porosity and permeability for the pay (the "tightest" a rock can be and still yield hydrocarbons), derived empirically, are 13% and 1.0 millidarcy. Generally,the best producers are the most porous.

Visual and scanning electron microscopy (SEM) of core thin sections cut from nine Knutson area wells show that porosity is essentially all intercrystalline, and that porosity increases as a function of the degree to which calcite has recrystallized to dolomite. X-ray diffraction (XRD) work shows some of the rock to be more than 90% dolomite, and that dolomites are the most porous. Furthermore, dolomitization appears to have been fabric-selective, lime mud being preferentially recrystallized.

No more than traces of clay minerals or detrital quartz showed up in the SEM or XRD work that was done. Presumably, gamma radiation, detected by logs through the Mission Canyon, was released by elements other than potassium, a clay constitutent.

THE MISSION CANYON PLAY

What began for Diamond Shamrock as a simple structural prospect to evaluate a randomly-acquired leasehold has evolved into a combination trap concept incorporating three trapping mechanisms: structure, stratigraphy, and hydrodynamics. Previous writers, Altschuld and Kerr (1982), Berg and Mitsdarffer (1986), Kupecz (1984) and Mitsdarffer (1985), studied these mechanisms and their effects on the Billings Nose complex, a Mission Canyon accumulation of some 65 million

primarily-recoverable barrels of oil. For a modest-sized company like Diamond Shamrock, however, the discovery and operation of the 4 million barrel accumulation at Knutson required more than the usual geologic glance before racing to the next prospect.

Accordingly, a regional Mission Canyon study was undertaken, the outline of which is shown on Figure 1. Regional Mississippian stratigraphic sections were constructed, the remaining wildcats correlated, the fields detailed, and two maps made, Figures 4 and 6. Additional detailed maps were prepared on Knutson field, Figures 5, 8, 9, 11 and 13, and on the Billings Nose area, not herein reproduced.

STRUCTURE

Mississippian structure of a part of south-central Williston Basin is presented on Figure 4. Only Mission Canyon oil fields are shown. The Billings Nose complex is labelled with its five component fields: T-R, Big Stick, Four Eyes, Tree Top and Whiskey Joe. Small portions of two other large fields, Elkhorn Ranch and Little Knife, appear on the northern edge of the map. Note that Knutson field consists of separate north and south pools.

Structural closure is not necessary to trap hydrocarbons in this Mission Canyon play. Even if 10 foot contour intervals had been used only Medora, West Fryburg, and Bullsnake fields would have revealed closure (Fig. 4). Figure 4 secondly demonstrates that the largest fields lie along three regional north-plunging anticlinal noses: West Fryburg-Whiskey Joe-Tree Top, Medora-T-R-Big Stick-Four Eyes, and Square Butte-Knudson.

The Knutson field structure is shown in greater detail (Fig.5.) All producing wells shown are productive from the "Knutson" except the Red River producer in Section 30, T141N, R102W, and a "First Fryburg" well in Section 25, T140N, R103W. Contours on the west flank of the north pool structure are largely defined by seismic. Key observations on Figure 5 are the lack of structural influence on the south pool, and the asymmetric (east flank) position of the north pool.

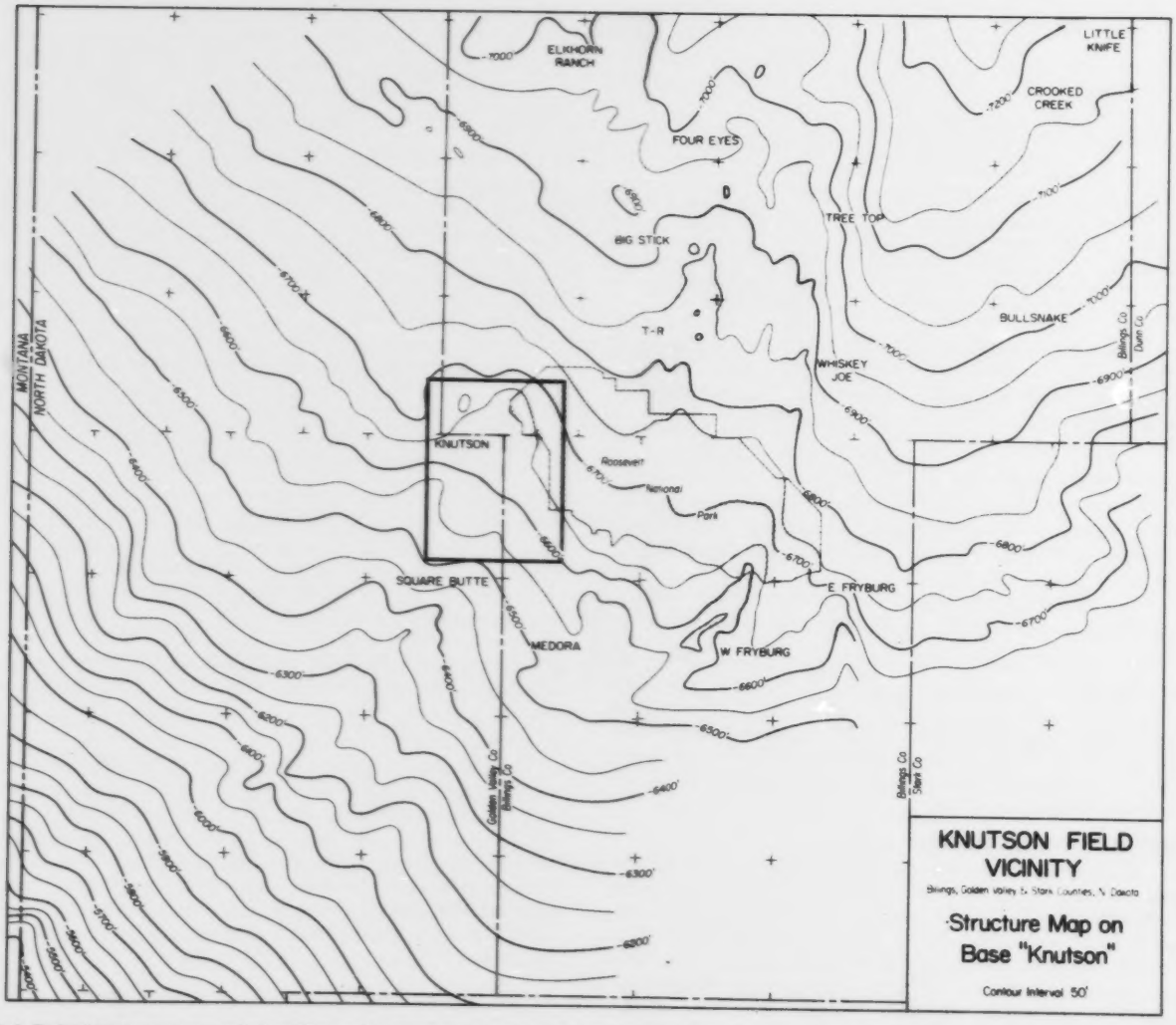


Fig. 4 Regional structure contour map. Outline of Knutson field maps (Figs. 5 and 8) shown in box. Significant Mission Canyon oil fields shown by shading.

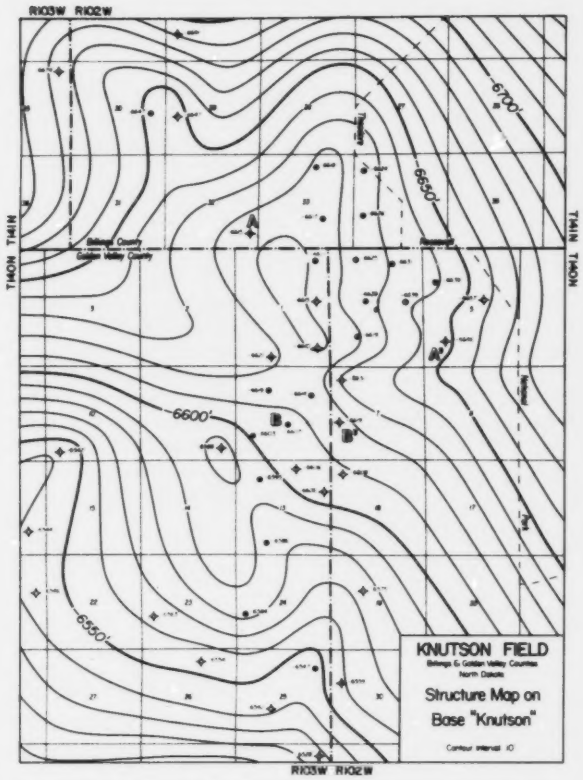


Fig. 5 Knutson field structure contour map. Note lines of cross-section A-A' and B-B'

In summary, the role of structure in Knutson field and in the Mission Canyon play in general is the focusing of hydrocarbon migration. Four-way closure, however, is not a prerequisite for entrapment, and production is sometimes associated with a lack of even two-way reversal.

STRATIGRAPHY

The Mission Canyon Formation in this area was deposited in and adjacent to a shallow, restricted and regressive sea, far removed from terrigenous sediment sources. Bordering the sea on the southeast were tidal flats and a low-relief sabkha. The seafloor sloped gently northwest, and the NE-SW-striking shoreline migrated episodically into that marine basin.

The resultant rock sequence consisted of 300 to 400 feet of original calcareous sediment and rock of variable texture (the "lower carbonate" facies) overlain by 0 to 120 feet of evaporitic facies, the "Nesson" anhydrite. Magnesium-enriched brine, derived from precipitation of gypsum and anhydrite in the sabkha, subsequently dolomitized much of the original calcite in the lower carbonate facies.

HYDROCARBON RESERVOIRS

The upper, and economically-significant, portion of the two Mission Canyon facies is the "Knutson" (Fig. 2). The lower carbonates consist of alternating and laterally-continuous horizons of porous dolomite and nonporous limestone. The porous horizons, as discrete units, pinch out to nonporous limestones towards the southeast (landward). Because of regressive deposition, the units "shingle out"; that is, the pinchout of the uppermost unit occurs northwestward of that of the next-lowest unit.

Two lines of pinchout, those of the "Knutson" and "First Fryburg" horizons, are shown by heavy tick-marked lines (Fig. 6). Mission Canyon oil production in this area corresponds to these two pinchout lines. Oil produced from wells located northwest of the "Knutson" pinchout comes mostly through perforations in the "Knutson." Mission Canyon production located between the "Knutson" and "First Fryburg" pinchout lines is primarily from the "First Fryburg." Wells located southeast of the "First Fryburg" pinchout yield oil from porous horizons stratigraphically below the "First Fryburg."

While the primary pay in any well is normally the stratigraphically-highest porous horizon, oil may sometimes also be recovered from lower horizons in oil fields with exceptionally-large structural reversal. This is the case in part of T-R and Little Knife fields. Except for one well, Knutson field seems to lack sufficient structural size for lower zones to be significantly productive.

"ANHYDRITE" MAPPING

Figure 6 is an attempt to relate a mappable quantity, the proximity of the lowest Nesson anhdyrite facies to the "Knutson" horizon (see Fig. 2), to a quantity that is not mappable without 160-acre well control, namely reservoir porosity. This map is a hybrid of another, more common, map, the gross "Nesson" anhydrite isopach, both of which require density log control, and both of which presume a relationship between the anhydrite development and underlying dolomite development. The version used here is somewhat customized to the "Knutson" horizon and is not affected by fluctuations in the stratigraphic position of the top of the Nesson anhydrite. The arbitrary density porosity cutoff used here, -6%, may be too large for actual anhydrites, but is a convenient indicator of dense and probably-anhydritic rock.

The interval isopached in Fig. 6 thickens regionally to the northwest, corresponding to the migration in that direction of the sabkha shoreline. This regional isopach thickening is demonstrated in the locality of Knutson field by cross-section A-A', Figure 7. The line of this cross-section is shown on Figure 8. Notice that on A-A' the isopach values increase to the northwest (left) from 18 feet to 48 feet.

Figure 6 displays an irregularity of contour spacing which the authors attribute to the episodic nature of northwesterly shoreline migration in response to eustatic change. Widely-spaced contours signify rapid regression. Conversely, areas of close contours were areas of relative shoreline stabilty. One such stillstand occurred near the area bounded by the 25 and 50 foot contours. Within this area, the isopachous "fault" shown running through Big Stick field toward Tree Top field is a contouring artifact which demonstrates that regression was locally interrupted by a minor but significant transgression.

The shoreline stillstand represented by the 25 to 50 foot isopachs on Fig. 6 gave rise to the best reservoir development in the study area, and consequently to the best oil wells. These results may have been achieved in two ways. First, a stable shoreline may have allowed deposition of thicker-than-normal accumulations of lime mud. Second, a stationary period may have allowed more time for percolating magnesium brine to work on the sediment, thereby increasing the dolomite-to-limestone ratio.

The inferred relationship of the isopach map (base-anhydrite-facies-to-base-"Knutson"-horizon) to "Knutson" porosity development may be seen by comparing Figures 8 and 9.

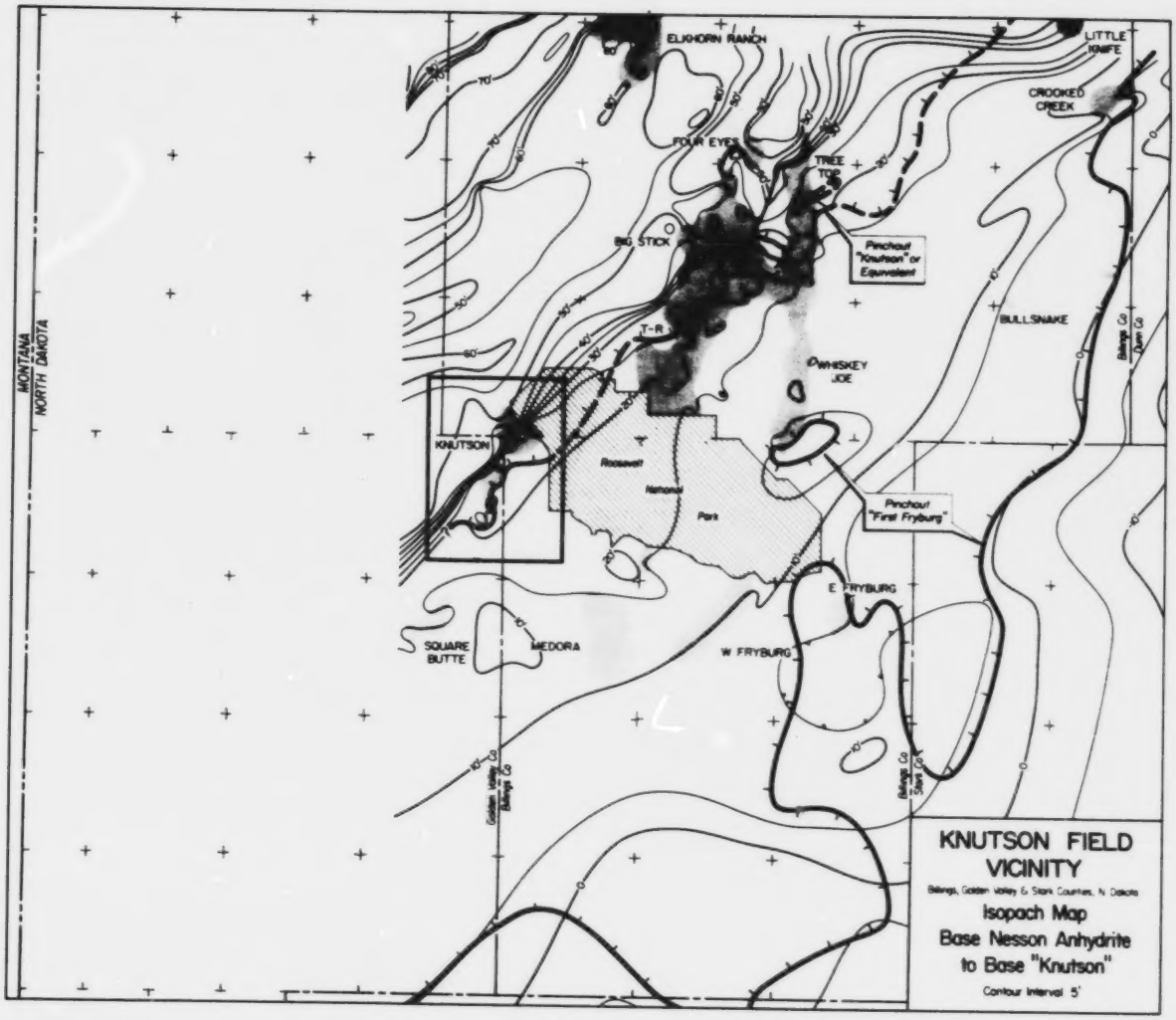


Fig. 6 Regional isopach map of interval shown on Fig. 2. Outline of Knutson field isopach (Fig. 8) shown in box. Heavy "tick-marked" lines denote pinchout of Knutson and First Fryburg effective porosity. Tick marks point towards porosity development. Negative contours in lower right of map represent area where the lowest Nesson Anhydrite crosses the base of Knutson gamma-ray marker. These contours still represent the interval between the base of the anhydrite and the base of the Knutson zone, but denote the anhydrite is below the base of the Knutson.

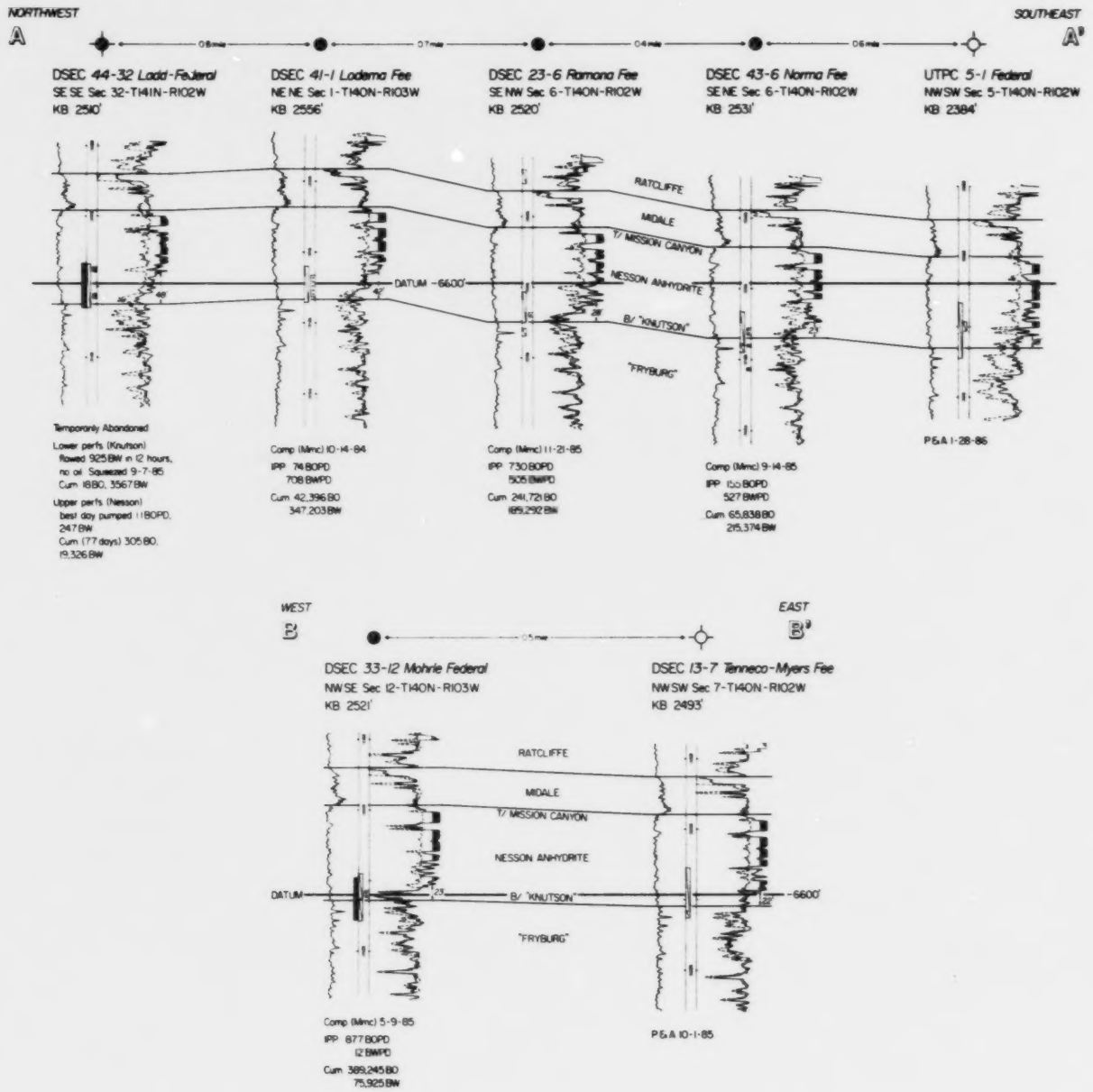


Fig. 7 Structural cross section "hung" on a datum of -6600' mean sea level through lower Charles and upper Mission Canyon Formations, Knutson field. See Fig. 5 for location of cross-section lines. All logs are GR-FDC-CNL. Values are shown for the interval which is isopached in Fig. 8.

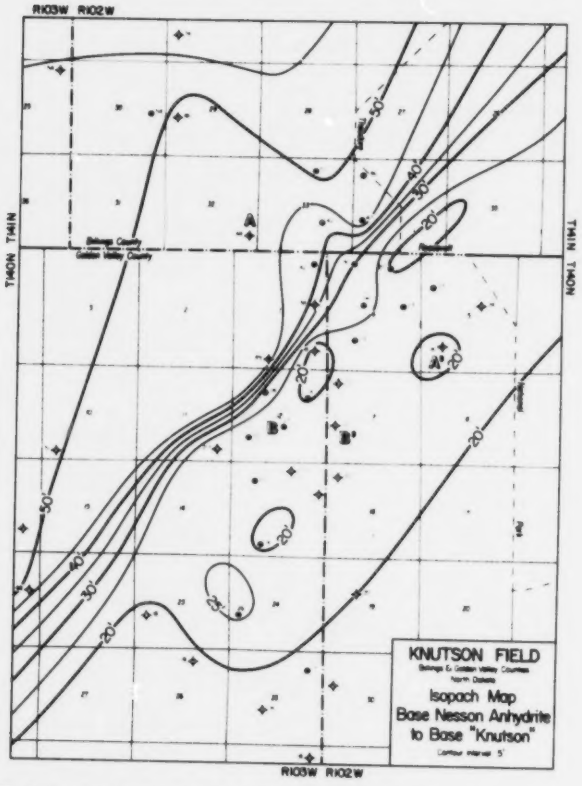


Fig. 8 Knutson field isopach map of interval shown on type log (Fig. 2) and cross-sections (Fig. 7).

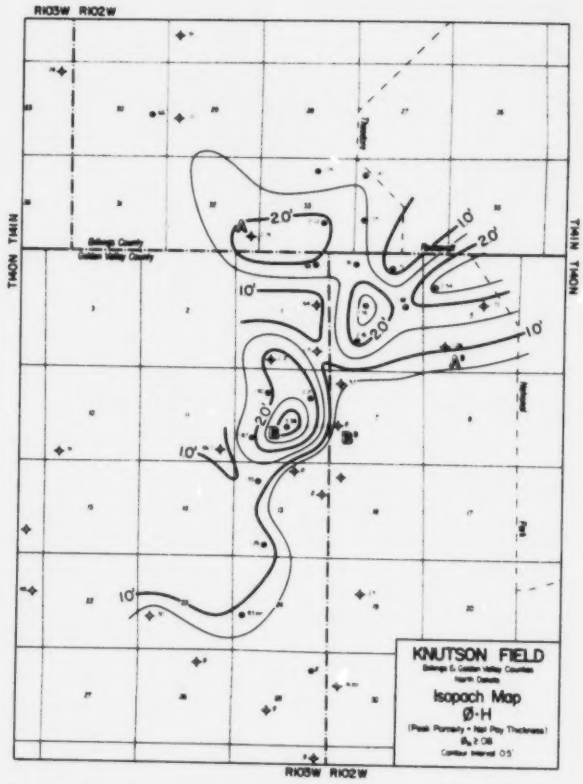


Fig. 9 Isopach map of net reservoir in Knutson field. Contour values are the product of peak crossplot porosity and thickness of neutron porosity in Knutson interval greater than 8%.

The best reservoir development in the field, in Figure 9, seems to occur within the 23 to 30 foot isopach values on Fig. 8. The porosity pod occurring in sections 32 and 33, seaward of the latter trend, suggests there may be other pods north and west of the field.

ENVIRONMENTAL MODEL

Detailed porosity mapping of the "Knutson" interval (Fig.9) plus unpublished Billings Nose maps reveals a reservoir distribution with the following charactertistics: a NE-SW-trending corridor up to five miles wide, with an often abrupt southeast (landward) margin (Fig. 7, B-B') and sporadic, cross-cutting non-porous trends. In their discussion of Little Knife field, Lindsay and Roth (1982) proposed a Mission Canyon depositional model which is applicable to the area studied in this paper. At the heart of their model was a wide, NE-SW-trending "protected shelf," bordered on the northwest by a "high-energy, open-marine" belt on the outer shelf, and on the southeast by an intertidal, restricted-marine belt adjacent to the "coastal sabkha." This protected shelf was the probable setting for deposition of lime muds and bioclastic wackes that were preferentially dolomitized, becoming the reservoirs of today. Kupecz (1984) arrived at similar conclusions in the Billings Nose area regarding the Mission Canyon depositional environment.

There are "tight" trends cutting across the NE-SW trending porosity corridor previously described. These may be seen as the re-entrants of the "Knutson" pinchout line into Big Stick and Tree Top fields (Fig. 6) and the low-porosity "saddle" at the common corner of sections 6, 7, 1 and 12 which separates the north and south pools (Fig. 9). These "tight" trends may be tidal channels that were filled with coarser-grained material than the sediments of the protected shelf, and were hence less dolomitized. Since these low-porosity channels are not reflected by the isopach contouring (Fig. 6 or 8), they represent an additional prospect risk.

In summary, isopach mapping may aid in highgrading areas in the search for reservoir rock. The area defined by the 25 and 50 foot isopach contours (Fig. 6), between Knutson field and Little Knife field, contains 80% of the best Mission Canyon oil wells in the study area. This is the case not because of superior structure, but because of superior reservoir.

HYDRODYNAMICS

Hydrodynamics modify pre-existing hydrocarbon accumulations in Knutson field, as well as in the Billings Nose complex (Mitsdarffer, 1985; Berg and Mitsdarffer, 1986), and, in so doing, complicate log calculation of water saturation in this area. To understand the processes involved, it is appropriate to review the regional hydrodynamic setting.

In 1984 the U.S. Geological Survey published a Professional Paper dealing with aspects of the Madison and other aquifers in the northern Great Plains (Downey, 1984). This work was done to evaluate the water resources available for a potential massive coal development project in western North Dakota, eastern Montana and northwestern Wyoming.

Madison (Mission Canyon) groundwater salinity was contoured from borehole data points around the region (Fig. 10). The arrows indicate the general direction of groundwater flow, away from mountainous outcrop areas in the southwest, and towards aquifer discharge areas in the eastern Dakotas and Manitoba. Meteoric water increases in salinity as it picks up

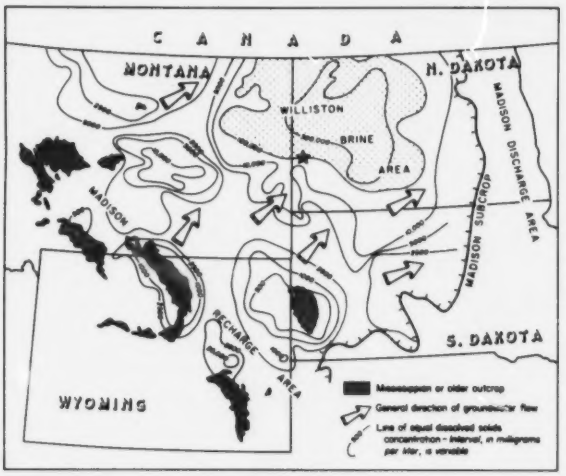


Fig.10 Regional salinity map. Knutson field shown by star. Arrows indicate direction of Mission Canyon ground water flow (modified from Downey, 1984).

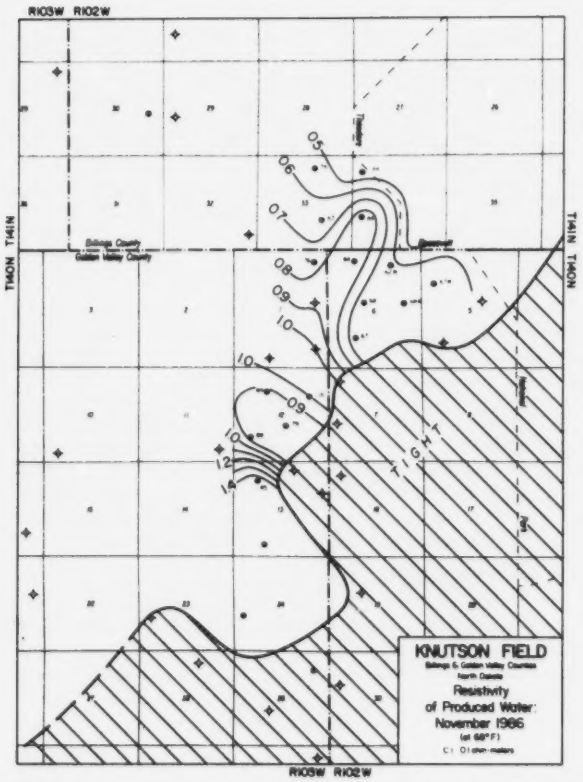


Fig. 11 Map showing resistivity (R_w) of produced water. Values are lab observed R_w's at 68 degrees Farenheit. Asterisk (*) indicates well whose perforations include Fryburg zones. Samples taken from wells November 23, 1986.

soluble salts from the Madison sediments. Salinity increases rapidly when, at the margin of the Williston Basin, groundwater encounters massive halite beds in the upper Madison (Charles Formation).

Knutson field (Fig. 10, star) is located on the leading edge of the resulting Mission Canyon brine area. Salinity changes observed at Knutson are consistent with the flow of groundwater from the southwest that Downey (1984) described. These salinity changes are of three types: lateral, temporal and vertical.

Lateral changes in salinity were noted with a general trend of increasing salinity to the northeast (Fig. 11). This trend supports the idea of freshwater invasion from the southwest (as in Fig. 10). Further evidence of this "freshwater plume" can be seen in the temporal data (Fig. 12). All wells show a freshening-with-time pattern. The freshwater influx into the south pool is more rapid than that into the north pool.

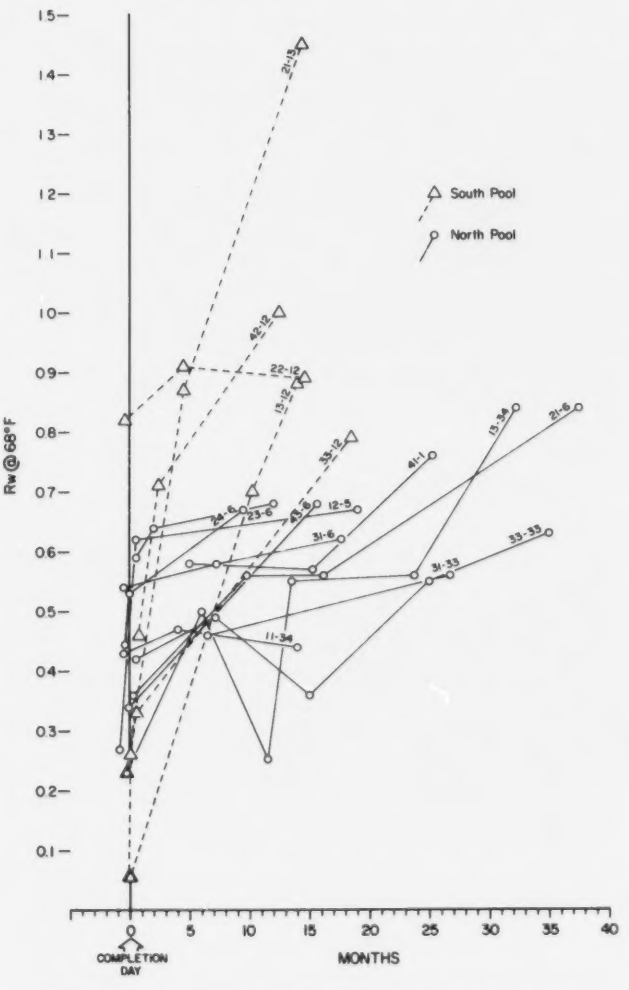


Fig.12. Graph showing resistivity of produced water as a function of time for individual wells in Knutson field. Values are lab-observed R_w's at 68 degrees Farenheit.

R_w stratification, specifically an apparent freshening-down trend, is the third indicator of freshwater influx. As mentioned previously, drillstem and production testing have proven that in Knutson field, only the "Knutson" bears significant hydrocarbons. The "Fryburg" zones are wet. Yet, for individual wells, assuming constant Mission Canyon R_w results in uniform apparent water saturations for the upper "Fryburg" as well as "Knutson." A higher (fresher) R_w is required for the

"Fryburg" than for the "Knutson" to match test results. The authors speculate the "Fryburg" zones have been flushed to a greater degree than has the "Knutson" by freshwater influx because the "Knutson" zone within the field has been sheltered by a proven structural/stratigraphic trap.

The most important and economically-significant evidence for freshwater invasion is tilting of the apparent oil-water contact in Knutson field. Because of the heterogeneity of carbonate porosity distribution in the Mission Canyon play, and because of imprecision in determining R_w, oil-water contacts cannot be picked from logs. In models like Knutson, and larger accumulations, however, produced water cut from wells of like porosity can be compared to create an apparent or "economic" oil-water contact.

Figure 7 (A-A') displays five wells of similar porosity in structural cross-section. The UTPC 5-1 Federal, although marginally porous, is structurally low and is shown clearly by drillstem test to be wet. Comparison of daily and cumulative production data from the remaining wells shows the 23-6 Ramona Fee to be the best well, with the lowest water cut, followed by the 43-6 Norma Fee, downdip. The two northwesterly wells are highest, both displaying respectable porosity and commensurate fluid deliverability, and yet are both wet. Indeed, the 41-1 Lodema Fee is the highest producer in the North Pool (Fig. 5) and yet has yielded more water than any other well in that pool (Table 1).

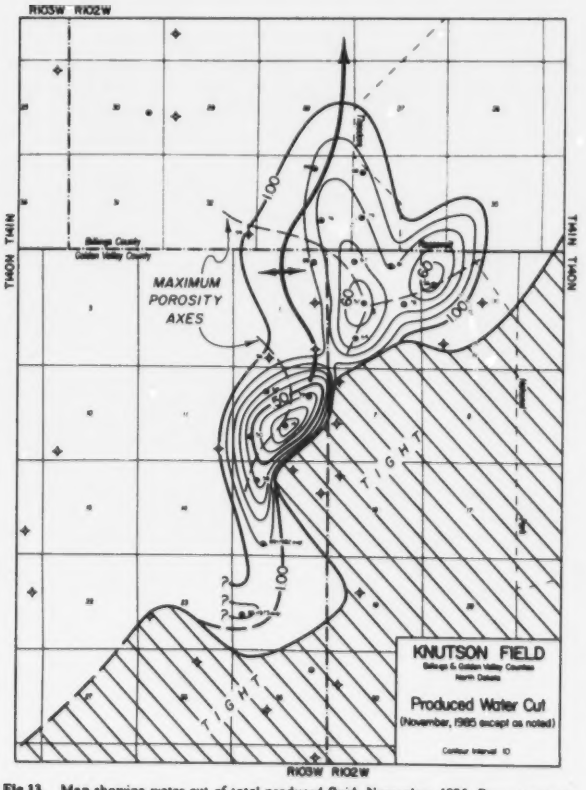


Fig.13. Map showing water cut of total produced fluid, November, 1985. Percentages are expressed as decimals (.80 = 80% water). Average well age at that time was eight months. Older Rider field wells in sections 13 and 24 are incorporated by averaging their water cuts for their first full year of production. Value from non-producers estimated from production and drill stem tests. Heavy line is the structural axis of the field (Fig. 5). Dashed line is zone of maximum porosity from Knutson interval.

Figure 13 illustrates in map view the theme of the preceding two paragraphs. On this map, well quality is quantified by produced water cut, with the .90 contour representing the field's empirical economic limit. Well quality generally conforms well with trends of maximum porosity, except in the areas of the two cased failures (wet) in sections 32 and SW 1/4 of 1. Notice especially the eccentricity of the North Pool with respect to the anticlinal axis.

A material balance evaluation performed by Diamond Shamrock, which related reservoir pressure decline to total fluid withdrawal, concluded that either the oil accumulation was immense and undeveloped, or it was receiving a substantial influx of formation water from outside the developed area. Since the tests in sections 1 and 32 had established the nearby presence of a large, permeable and water-filled reservoir, the evaluation further concluded the field recovery was benefiting from a water drive.

The authors conclude that invasion from the southwest by relatively fresh water from the Mission Canyon aquifer has tilted the North Pool oil accumulation onto the structural east flank. The authors further speculate that associated water-washing has stripped the accumulation of some of its lighter hydrocarbons, lowering the API oil gravity and gas-oil ratio, and thereby increasing the BTU content of remaining gas.

SUMMARY

In Knutson field, the authors find striking similarities to the factors which affect Mission Canyon hydrocarbon accumu-

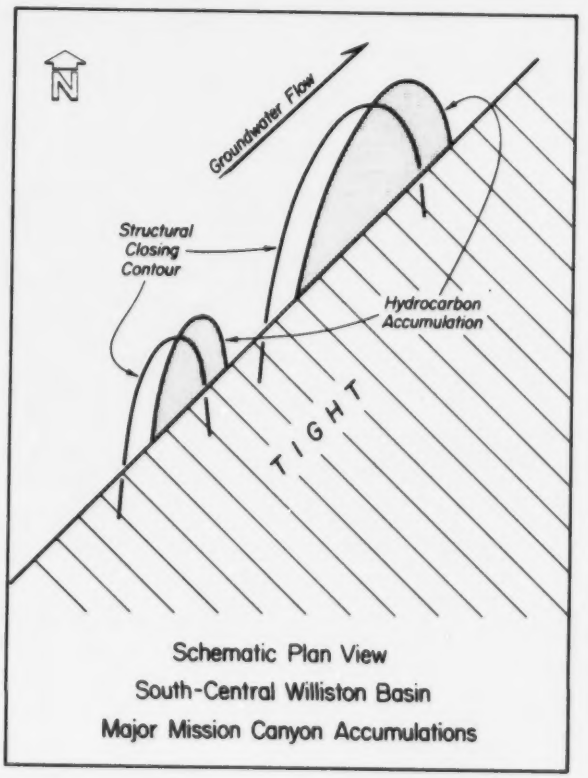


Fig. 14 Idealized model of three trapping mechanisms in Mission Canyon play, south central Williston Basin: structure, stratigraphy, and hydrodynamics.

lation in the fields of the Billings Nose complex and Little Knife. First, there is in common a series of north-plunging anticlinal noses generally exhibiting a lack of significant closure. Second, there is the southeasterly pinchout of key porous horizons, collectively referred to here as "Knutson," that may be related to a stillstand of an otherwise regressive shoreline. Results of Diamond Shamrock core and log studies of the "Knutson" horizon compare well with similar work by Lindsay and Roth (1982) in Little Knife, and Kupecz (1984) on the Billings Nose. Third, northeasterly hydrodynamic flow within the Mission Canyon has tilted part of the Knutson accumulation onto its structural east flank. This is similar to observations of Mitsdarffer (1985) and Berg and Mitsdarffer (1986), regarding the Billings Nose.

A model for this play is shown in Figure 14. Hopefully, consideration of this model will improve the results of drilling in the Mission Canyon of the south-central Williston Basin.

ACKNOWLEDGEMENTS

This paper is a synthesis of three years' work by many individuals at Diamond Shamrock Exploration Company, Denver. Its observations and conclusions are offered in a spirit of cooperation with others engaged in petroleum exploration. Accordingly, the authors wish to thank the management at Diamond Shamrock for permission to share these ideas. We gratefully acknowledge the assistance of Eric Mansanarez and Denise Garvey of Diamond Shamrock in preparing the exhibits and text.

The authors also wish to thank those people with the U.S. Bureau of Land Management, Billings, who provided critical review of the final manuscript.

REFERENCES CITED

Altschuld, N., and Kerr, S.D., Jr., 1982, Mission Canyon and Duperow reservoirs of the Billings Nose, Billings County, North Dakota, In: Christopher, J.E., and Kaldi J., eds., Fourth International Williston Basin Symposium: Saskatchewan Geol. Soc., Special Publication Number 6, p. 103-112.

Berg, R.R., and Mitsdarffer, A.R., 1986, Effects of hydrodynamic flow on carbonate stratigraphic traps, Mission Canyon Formation, Billings Nose Fields, North Dakota (abs): AAPG Bull. vol. 70, no. 5, p. 564.

Downey, J.S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.

Kupecz, J.A., 1984, Depositional environments, diagenetic history, and petroleum entrapment in the Frobisher-Alida interval, Billings Anticline, North Dakota: Colorado School of Mines Quarterly, Vol. 79, No. 3, 53 p.

Lindsay, R.F., and Roth, M.S., 1982, Carbonate and evaporite facies, dolomitization and reservoir distribution of the Mission Canyon Formation, Little Knife Field, North Dakota, In: Christopher, J.E., and Kaldi J., eds., Fourth International Williston Basin Symposium: Saskatchewan Geol. Soc., Special Publication Number 6, p. 153-179.

Mitsdarffer, A.R., 1985, Hydrodynamics of the Mission Canyon Formation in the Billing Nose Area: Unpublished M. S. Thesis, Texas A&M University, 162 p.

FAMILIES OF OILS IN SOUTHEASTERN SASKATCHEWAN *

P.W. BROOKS, L.R. SNOWDEN AND K.G. OSADETZ

Institute of Sedimentary and Petroleum Geology
3303 33rd St. N.W.
Calgary, Alberta, Canada
T2L 2A7

ABSTRACT

Three compositionally distinct families of oils are recognizable from 34 samples produced from a representative suite of pools in southeastern Saskatchewan. The families are characterized by gross geochemical and C_{15+} saturate hydrocarbon fraction compositions, obtained by gas chromatography and mass spectrometry-gas chromatography.

Family A (2 pools) oils are characterized by low pristane/ nC_{17} and phytane/ nC_{18} ratios, high diasterane/ regular sterane ratios and low C_{23}/C_{30} terpane ratios. This family of oils is restricted to Ordovician pools. It is identical to the oils from Ordovician reservoirs in the American portion of the Williston Basin. Family B oils (9 pools) are characterized by cross-plots of the ratio of diasteranes/ regular steranes against either the ratio of saturate/aromatic hydrocarbons or the ratio of pristane/ phytane. Within Family B a group of oils (4 pools) with low C_{23}/C_{30} terpane ratios may represent a mixture of oils from families B and A. Family B oils are restricted to pools in the Birdbear Formation, the Bakken Formation and the Madison Group. The most abundant family of oils, Family C (22 pools), is identified by the same criteria used to characterize Family B oils, although they have low diasterane/ regular sterane ratios and low pristane/ phytane ratios in comparison to Family B. Family C occurs in the Madison Group and younger reservoirs. A distinctive sub-group of oils in Family C has high saturate/aromatic hydrocarbon ratios. One oil with an intermediate diasterane/ regular sterane ratio may represent a mix of oils from families B and C.

Oils in Families B and C have been previously included in a single family of oils attributed to a Bakken source rock. However, the stratigraphic distribution and compositional characteristics of Family C oils preclude such a derivation. The Madison Group is a more likely source. The Bakken Formation remains a potential source for Family B. Family A is probably derived from an Ordovician source rock.

Other families of oils recognized in the American portion of the Williston Basin are not recognized in southeastern Saskatchewan.

INTRODUCTION

Oil was discovered in the Canadian portion of the Williston Basin in 1951 at Daly Manitoba (McCabe, 1963). Discoveries near Ratcliffe and Wapella in the following year (Fuller, 1956) began the exploitation of oil resources in southeastern Saskatchewan that have resulted in the identification of an initial recoverable reserve of approximately 226 million cubic metres of oil (Sask. Energy and Mines, 1984). This report examines the geochemistry of these oils with the purpose of determining their compositional characteristics, with particular emphasis on the C_{15+} saturate hydrocarbon fraction. The results of this study allow the grouping of the oils into families of similar composition.

Petroleum is produced from Paleozoic and Mesozoic formations in southeastern Saskatchewan (Figure 1) from an area roughly constrained by Range 25 west of the 2nd meridian (approximately 105 degrees west) on the west, the Manitoba border, Range 30 west of the prime meridian (approximately 101 degrees west), on the east, the border with the United States (49 degrees north), on the south, and Township 16 (approximately 50.5 degrees north), on the north. The producing formations in this study extend into Manitoba, North Dakota and Montana.

Williston Basin oils have been studied by several investigators. Williams' (1974) study of a widely distributed set of samples from both sides of the international boundary resulted in the identification of three families of oils of consistent chemical composition and restricted stratigraphic distribution. Using his classification: Type I oils are found in reservoirs of Ordovician to Mississippian age, Type II oils occur in reservoirs of Devonian, Mississippian and Mesozoic age, and Type III oils are restricted to pools in the Pennsylvanian Tyler Formation. The main criteria for this grouping included: carbon-isotope ratios of both whole oils and selected hydrocarbon fractions, and compositional variations of both gasoline range hydrocarbons (C_4-C_7), and heavy (C_{15+}) saturate fraction hydrocarbons. Zumberge (1983) employed a crossplot of the carbon-isotope ratios of C_{15+} aliphatic hydrocarbons against pristane/ phytane ratio in conjunction with normalized tricyclic terpane distributions to identify six different groups of oils. His Groups 1 and 2 appear to be identical to Williams' Type I and II oils. Among the other four groups are samples representing families of oils that are distinctive from those identified by Williams.

Both Leenheer (1984) and Price et al (1986b, 1984) described oils from the Williston Basin in studies that primarily examined the source rock potential of the Bakken Formation. Bailey et al (1973) described several oils from southeastern Saskatchewan and the effects of water washing and bacterial degradation along the Mission Canyon trend.

GEOLOGICAL SETTING

Reservoirs for oil in southeastern Saskatchewan lie within the Williston Basin, a Phanerozoic epicratonic basin situated near the centre of the North American craton. The stratigraphic succession (Fig. 2) is composed of five unconformity-bounded sequences. The oldest is part of the marginal clastic belt of the lower Paleozoic miogeocline of Western Canada, known locally as the Deadwood Formation. These strata are onlapped by shallow marine clastics (Winnipeg Formation) and carbonates (Bighorn and Interlake Groups) of the marginal clastic and medial carbonate belts of the Middle Ordovician to Silurian epeiric platform of eastern North America (Fuller, 1961). Middle Devonian strata representing part of the Taghanic onlap initiate the third depositional sequence. This sequence includes a largely conformable succession of Middle Devonian to Carboniferous rock. With the end of deposition

* Contribution of the Geological Survey of Canada

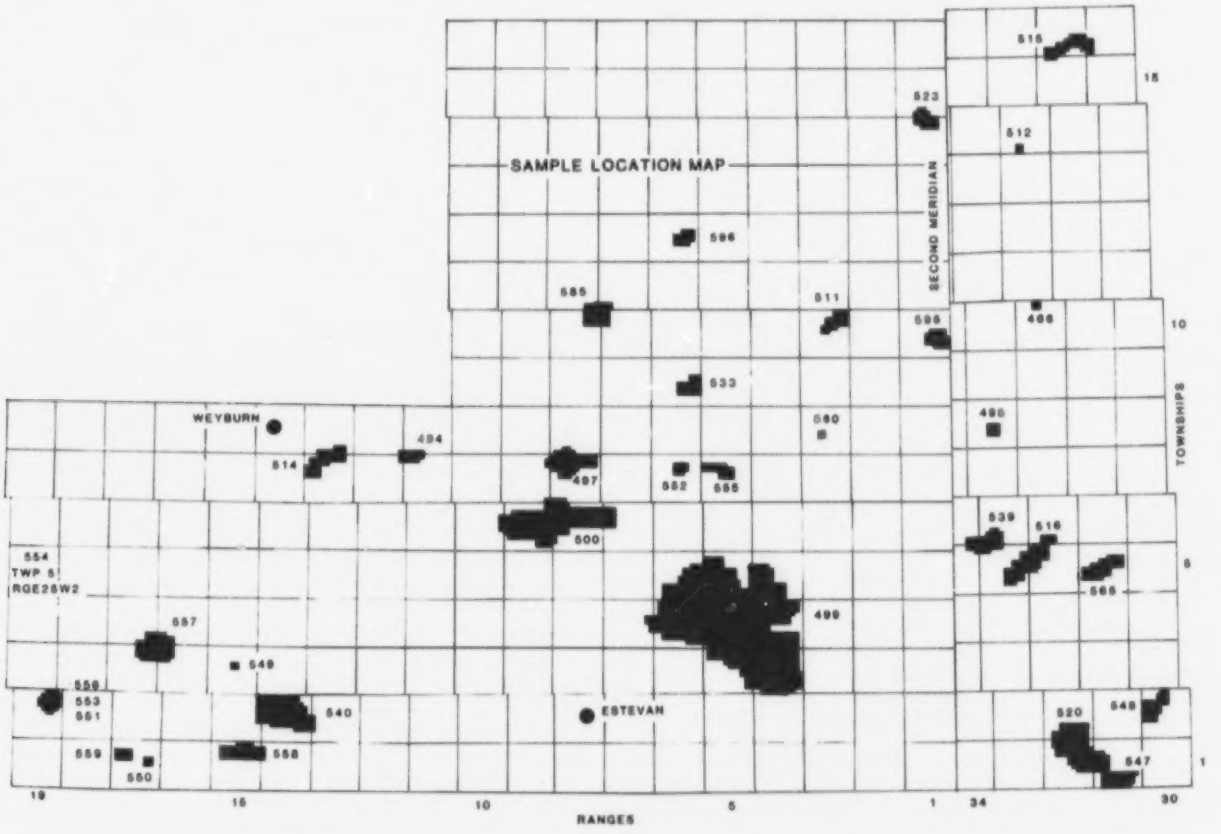


Fig. 1 Map of southeastern Saskatchewan indicating pools from which oil samples were collected for this study. Details of well locations and stratigraphic intervals sampled are given in Table 1.

	GROUP	PRODUCING ZONE	OIL SAMPLE
CRET.	MONTANA		
	COLORADO		
	MANNVILLE	WAPELLA SAND	533
JURASSIC	VANGUARD		
		SHAUNAVON FM.	512
		GRAVELBOURG FM.	
		WATROUS FM.	560
CARBONIFEROUS	MADISON	POPLAR BEDS	
		RATCLIFFE BEDS	540,559,557,550,559
		MIDALE BEDS	499,500,514,547
		FROBISHER BEDS	494,497,516,520,533,
		ALIDA BEDS	539,548,555,535
		TILSTON BEDS	498,511,498,595,599
		SOURIS VALLEY BEDS	
DEVONIAN	THREE FORKS	BAKKEN FM.	516,559,554
	SASKATCHEWAN	BIRDBEAR FM.	406,551,553
	MANITOBA		
	ELK POINT	WINNIPEGOSIS FM.	
SIL.	INTERLAKE		
ORD.	BIGHORN	RED RIVER FM.	548, 550
	WINNIPEG		

Fig. 2 Schematic stratigraphic table indicating the relative stratigraphic position of oils samples listed in Table 1.

in Carboniferous time an extensive erosional surface was developed across the southerly dipping strata. Sedimentation resumed in the Jurassic and a mixed succession of evaporites, carbonates and clastics were deposited. These are overlain unconformably by Cretaceous and Cenozoic clastics deposited in the Cretaceous interior seaway and as molasse of the Western Cordillera.

The oldest producing strata within the study area are platform carbonates of the Upper Ordovician Bighorn Group. A well only recently completed in the Middle Devonian Winnipegosis Formation is confidential.

The next is the Birdbear Formation, a carbonate, which lies near the top of the Devonian carbonate succession. Massive Devonian carbonates are separated from Carboniferous carbonates by the carbonate-evaporite and clastic strata of the Three Forks Group that includes the transitional Devonian-Mississippian Bakken Formation. Production is also obtained from the middle sandy member of the Bakken Formation at three pools widely separated across the study area.

The carbonates of the Carboniferous Madison Group contain most of the oil reserves in southeastern Saskatchewan. Oils are primarily entrapped at or near the subcrop edge below Mesozoic formations. Madison strata are a dominantly off-lapping carbonate-evaporite succession, within which the onlap of subtidal carbonates over evaporites is cyclic (Fuller, 1956; Edie, 1958; Fuzesy, 1960). Oil is entrapped in porous carbonate strata occurring between the evaporitic members (Kent, 1984).

While most oil pools in the Madison Group are entrapped by seals at or near the subcrop edge of carbonate members, other pools are different. Those of the Ratcliffe Beds on the Oungre Trend are in place against a subtle stratigraphic-diagenetic trap (Hartling et al, 1982). Other Ratcliffe and Midale Beds pools are structurally controlled and genetically associated with underlying solution of the salt beds of the Middle Devonian Prairie Formation. Traps of this type are caused by structural inversion due to repetitive salt solution, as at Hummingbird (Smith and Pullen,1967), or by closure formed by updip solution of salts as is the case at Hoffer (Hartling et al, 1982). Pools controlled by salt solution processes are likely to be in communication with deeper horizons through related faulting.

The youngest reservoirs of oil in southeastern Saskatchewan occur in Jurassic and Cretaceous sands. These oil pools are situated in the northeast of the area of study where the Mesozoic is thin and condensed. Oil pools occur in several configurations; however, it is commonly held that these pools represent migration of oils underlying Carboniferous reservoirs (Barchyn, 1984; Van Delinder, 1984).

EXPERIMENTAL WORK

A total of 34 oils from southeastern Saskatchewan, covering a wide range of geographic localities and all stratigraphic settings except the Winnipegosis (Table 1), were fractionated, following distillation to remove material boiling below 210 degrees Celsius, according to the method published by Snowdon (1978). Saturate hydrocarbon fractions were examined by capillary column gas chromatography (GC) using a VARIAN 3700 GC equipped with a 25 m fused silica column coated with OV-1 and temperature programmed from 50-280 degrees Celius at a heating rate of 4 degrees per minute using He as the carrier gas. Capillary column gas chromatography-mass spectrometry (GC-MS) of both the saturate and aromatic fractions was performed using a KRATOS MS-80RF mass spectrometer under the control of a DS-55 data system. GC conditions were typically: J and W 25 m DB5 column temperature programmed from 50-320 degrees Celcius at 4 degrees per minute and coupled directly to the source of the mass spectrometer. MS conditions were typically: 300 microA filament emission current and 70 eV ionization potential. Data were collected either by collection of full mass spectra scanning from m/z 650-50 at 1 second/decade or by multiple ion detection (M.I.D.) monitoring ions at m/z = 177.1638, 191.1794, 217.1950, 218.2028, 231.2106, and 259.2262.

RESULTS

Based on the results of this study the oils of southeastern Saskatchewan are divided into three families: A, B, and C. Two oils are assigned to Family A, nine are assigned to Family B, twenty-two are assigned to Family C, and one oil appears to be clearly a mixture of oils from families B and C. Mixing of oils from different families may be more widespread although, if this is so, it appears that mixing occurs on a minor scale that does not mask the dominant familial affinity of the oil. It is convenient to discuss the characteristics of the oils within the context of the familial groupings.

GROSS GEOCHEMICAL COMPOSITION

The gross composition of the oils studied are listed in Table 2. Oils assigned to Family A are characterized by a low saturate/aromatic ratio (less than 0.90) and high contribution of asphaltenes (12 per cent and 24 per cent) by weight. Family B oils in the main, reveal low asphaltenes and a saturate/aromatic ratio greater than or equal to 0.90. Family C falls into two groups. A group of sixteen oils are marked by low saturate/aromatic ratios (less than one) and relative asphaltene abundances that are intermediate between those of families B and A. The other group has saturate/aromatic ratios that are greater than one and lower relative asphaltene abundances. In this respect the latter group of six Family C oils are similar to Family B, although in other respects they exhibit the gross compositional characteristics of Family C.

Table 1. Sample location information.

# Pool name	Producing Depth	Well Location	Producing Formation
466 NO POOL NAME	1075.5-1086M	05-33-010-32W1	Birdbear Fm
494 INNES WEST	1335.2-1335.6M	13-31-007-11W2	Madison Gp Frobisher Beds
495 SOUTH PARKMAN	3577-3581'	16-09-006-33W1	Tilston and Souris Valley Beds
497 VIEWFIELD	1349-1350.5M	13-33-007-08W2	Madison Gp Frobisher Beds
499 STEELMAN	1191.1-1199M	13-27-004-05W2	Madison Group Midale Beds
500 BENSON	1334.7-1335.9M	05-25-006-08W2	Madison Group Midale Beds
511 KENOSEE	1195-1198M	12-28-010-03W2	Madison Group Tilston Beds
512 RED JACKET	663-666M	10-04-014-32W1	Jurassic sandstone
514 RALPH	1306.7-1314.1M	01-32-007-13W2	Madison Group Midale Beds
515 ROCANVILLE	651-655.6M	02-11-016-31W1	Three Forks Gp Bakken Fm
516 NOTTINGHAM	1129.2-1137M	04-14-005-13W1	Madison Group Alida Beds
520 WORKMAN	1207-1216M	03-03-002-32W1	Madison Gp Frobisher Beds
523 WAPELLA	668.43-672.08M	13-34-014-01W2	Wapella sandstone
533 STAR VALLEY	3817.75-3824'	13-11-009-06W2	Frobisher and Alida Beds
539 ALIDA WEST	1130-1334.2M	06-06-006-33W1	Madison Group Alida Beds
540 OUNGRE	1820-1826.5M	03-29-002-14W2	Madison Group Ratcliffe Beds
547 ELMORE	1177-1183.6M	09-04-001-31W1	Madison Group Midale Beds
548 GAINSBOROUGH	3492'	07-28-002-30W1	Frobisher and Alida Beds
549 OUNGRE WEST	2929M-2936M	04-22-003-15W2	Bighorn Group Red River Fm
550 LAKE ALMA	3058-3065M	07-23-001-17W2	Bighorn Group Red River Fm
551 HUMMINGBIRD	2309-2318M	10-26-002-19W2	Birdbear Fm
552 KISBEY	1616-1625M	07-27-007-06W2	Birdbear Fm
553 HUMMINGBIRD	2221-2229M	05-26-002-19W2	Three Forks Gp Bakken Fm
554 RONCOTT	1823-1825M	09-34-005-25W2	Three Forks Gp Bakken Fm
555 CLAIRLAW	1230-1233M	05-29-007-05W2	Frobisher and Alida Beds
556 HUMMINGBIRD	1876-1904M	11-26-002-19W2	Madison Group Ratcliffe Beds
557 NEPTUNE	1748.5-1755.5M	04-06-004-16W2	Madison Group Ratcliffe Beds
558 HOFFER	6349-6382'	06-30-001-15W2	Madison Group Ratcliffe Beds
559 LAKE ALMA	1981-1987M	04-29-001-17W2	Madison Group Ratcliffe Beds
560 FREEMANTLE	3900-3907'	11-16-008-03W2	Watrous Formation
563 STORTHOAKS	1412-1422'	A09-17-005-31W1	Alida and Tilston Beds
565 HANDSWORTH	1177.2-1179.5M	A09-36-010-08W2	Madison Group Alida Beds
595 PARKMAN	1082-1083M	08-11-010-01W2	Madison Gp Souris Valley B
596 MOOSE VALLEY	1182-1185M	12-14-012-06W2	Madison Group Tilston Beds

SATURATE FRACTION GEOCHEMICAL COMPOSITION

The major characteristics of the saturate fraction gas chromatograms (SFGC) and saturate fraction mass spectra are listed in Table 3. Figure 3 shows the SFGC's of samples #550, #466, and #557, which were chosen to represent "end members" characteristic of Families A, B, and C, respectively. Family A oils feature a very low value for pristane and phytane, a high pristane/phytane ratio (>1.6), a high abundance of C_{15}, C_{17}, and C_{19} n-alkanes, and a low relative abundance of higher homologues (>nC_{22}) with an even/odd predominance.

Family B oils have a pristane/phytane ratio greater than 0.8, excepting sample #533. They are generally less waxy (higher nC_{17}/nC_{29}) than the oils in Family C. Pristane/phytane ratios of less than one and a higher relative abundance of n-alkanes of carbon number greater than nC_{22} characterize Family C oils. The higher homologues are distinguished by a pronounced even/odd predominance.

From the analysis of their saturated hydrocarbon biological markers by GC-MS, additional criteria to those provided by

Table 2. Saturate fraction geochemical composition

# ZONE	% SATURATES	% AROMATICS	% RESINS	% ASPHALTENES	SAT/ AROM
FAMILY A					
549 Red River	24.9	38.8	11.8	24.4	0.64
550 Red River	34.8	42.2	10.9	12.1	0.82
FAMILY B					
466 Birdbear	54.5	36.6	6.2	2.6	1.49
551 Birdbear	52.5	38.2	7.2	2.2	1.37
552 Birdbear	51.9	39.2	6.8	2.1	1.32
533 Frob./Alida	41.5	46.0	7.4	5.2	0.90
515 Bakken	48.6	42.0	6.9	2.6	1.16
554 Bakken	55.4	37.6	6.0	1.0	1.47
516 Alida	57.2	37.3	4.0	1.5	1.53
499 Midale	58.1	36.9	3.7	1.3	1.57
558 Ratcliffe	47.2	39.8	6.6	6.4	1.19
MIXED FAMILY B AND C					
553 Bakken	44.4	42.8	9.5	3.3	1.04
FAMILY C					
595 Souris Valley	51.0	35.7	5.4	2.9	1.43
495 Til./Souris V.	47.0	39.8	8.2	4.9	1.18
565 Alida/Til.	48.3	38.5	6.5	3.4	1.25
548 Frob./Alida	46.1	40.1	9.2	3.9	1.12
520 Frobisher	49.7	39.6	6.4	4.3	1.26
547 Midale	41.5	39.8	12.2	6.5	1.04
596 Tilston	40.4	44.7	7.8	3.4	0.90
511 Tilston	46.2	43.3	13.3	7.2	0.84
539 Alida	31.8	50.8	9.9	7.5	0.63
585 Alida	32.5	47.5	9.9	8.8	0.68
555 Frob./Alida	40.1	45.8	9.2	4.9	0.89
494 Frobisher	31.3	47.2	11.5	10.0	0.66
497 Frobisher	34.6	41.3	13.1	9.8	0.84
500 Midale	34.5	45.3	10.1	10.1	0.76
514 Midale	33.0	47.6	10.5	8.6	0.69
540 Ratcliffe	37.2	49.4	7.0	6.4	0.75
556 Ratcliffe	38.5	46.7	8.3	6.5	0.83
557 Ratcliffe	30.0	51.0	11.3	7.6	0.59
559 Ratcliffe	32.3	48.3	10.3	9.1	0.64
560 Watrous	37.9	44.9	10.1	6.9	0.84
512 Jurassic	34.8	46.1	10.6	8.6	0.75
523 Wapella	38.6	44.2	9.1	8.0	0.87

Table 3. Gross geochemical composition

#	Pr/Ph[1]	17/Pr[2]	17/29[3]	%C27[4]	%C28[5]	%C29[6]	dia/reg[7]	S/R[8]	ββ/R[9]	23/30[10]
FAMILY A										
549	1.29	21.76	64.3	30	13	57	2.36	1.05	1.67	0.01
550	1.53	22.21	19.5	34	15	51	1.73	1.25	1.61	0.03
FAMILY B										
466	1.47	1.55	11.6	34	14	52	1.21	0.59	0.74	0.04
551	1.20	1.34	6.1	35	16	49	1.51	1.01	1.08	0.08
552	1.17	1.82	5.1	37	14	49	1.14	0.94	1.17	0.07
533	0.76	2.48	5.5	39	23	44	1.93	0.96	1.01	0.05
515	1.52	1.64	18.2	43	14	42	1.17	0.77	0.91	0.61
554	1.76	1.78	12.1	40	17	43	1.43	1.13	1.06	0.40
516	0.87	2.99	34.9	34	12	55	0.99	0.98	1.32	0.45
499	0.87	3.00	5.1	36	14	48	1.21	1.59	1.77	0.69
558	0.97	2.12	3.1	25	11	63	1.53	0.93	1.62	0.19
MIXED FAMILY B AND C										
553	1.03	1.31	8.1	30	20	50	0.77	0.83	0.87	0.21
FAMILY C										
595	0.77	2.51	2.6	41	14	45	0.34	0.86	1.37	0.39
495	0.61	3.46	3.7	39	12	49	0.52	0.97	1.28	0.45
565	0.77	2.74	3.9	38	12	50	0.61	1.15	1.38	0.39
548	0.60	3.37	6.1	34	13	53	0.35	0.92	1.30	0.38
520	0.62	3.48	7.2	39	15	46	0.36	0.95	1.34	0.37
547	0.51	3.10	6.5	42	12	46	0.31	1.05	1.56	0.48
596	0.65	2.09	4.9	38	14	48	0.32	1.04	1.02	0.31
511	0.56	2.64	2.5	37	15	48	0.35	0.92	1.16	0.43
539	0.55	2.42	3.7	33	10	47	0.37	0.92	1.06	0.43
585	0.58	2.28	3.9	37	14	49	0.36	0.80	1.12	0.31
555	0.84	2.07	6.4	34	15	50	0.51	0.95	1.02	0.41
494	0.70	2.11	4.4	32	17	51	0.39	0.73	1.04	0.31
497	0.64	2.48	5.2	37	13	50	0.39	0.86	1.04	0.34
500	0.50	2.99	6.7	36	13	52	0.24	0.75	0.94	0.49
514	0.91	4.47	13.0	42	14	44	0.49	0.91	1.38	0.39
540	0.95	1.54	7.4	37	14	49	0.57	0.90	0.92	0.30
556	0.72	2.26	5.5	39	15	45	0.37	1.09	1.37	0.44
557	0.48	2.44	3.6	41	13	46	0.18	0.86	0.80	0.26
559	0.65	2.21	4.9	34	13	53	0.35	0.76	0.82	0.37
560	0.52	2.60	2.0	39	15	47	0.33	1.03	0.97	0.48
512	0.67	1.78	3.6	39	15	46	0.33	0.98	1.15	0.40
523	0.80	1.63	5.1	46	12	42	0.34	0.96	1.26	0.31

1 Pristane/Phytane ratio

2 nC_{17}/Pristane ratio

3 nC_{17}/nC_{29}

4 $C_{27}/(C_{27}+C_{28}+C_{29})$ steranes (per cent)

5 $C_{28}/(C_{27}+C_{28}+C_{29})$ steranes (per cent)

6 $C_{29}/(C_{27}+C_{28}+C_{29})$ steranes (per cent)

7 diasteranes/regular steranes

8 (20S)/(20R) 5α(H) C_{29} steranes

9 14β(H),17β(H)/(20R) 5α(H) C_{29} steranes

10 C_{23} tricyclic/C_{30} pentacyclic hopane

the SFGC's were obtained for distinguishing the families of oils in southeastern Saskatchewan. The low relative ratio of diasteranes/regular steranes is a critical factor by which Family C is distinguished from Families A and B (Table 3, Fig. 6). This is reinforced by pristane/phytane ratios of less than 0.8 from the SFGC's. Family A, under this criterion, is conspicious by its very low pristane and phytane. Family B, which commonly has pristane/phytane ratios greater than 0.8, can be subdivided into two groups, B(i) and B(ii), on the basis of the distribution of tricyclic and pentacyclic terpenoids. Figures 4 and 5 show the m/z 217 and 191 traces for samples #550 (Family A), #551 (Family B (i)), #554 (Family B (ii)) and #511 (Family C) (see Tables 4 and 5 for identified peaks).

Oils in all three families reveal a similar distribution among the various carbon number steranes. The C_{29} sterane is slightly predominant over the C_{27} sterane. Both Families A and B feature a high abundance of rearranged steranes (diasteranes) relative to the regular steranes. In contrast to Families A and B, Family C oils are low in rearranged steranes relative to the regular steranes.

The ratios of (20S)/(20R)5α(H)-C_{29} [(20S)/(20R)] and 14β(H), 17 (H)/(20R)5 (H)-C_{29} [β, β/R] steranes are indicators of the thermal maturity of these oils. The samples examined in this study exhibit a large variation in these ratios. For example, the value of (20S)/(20R) for oil #559, a member of Family C, is 0.76, which indicates relative immaturity.

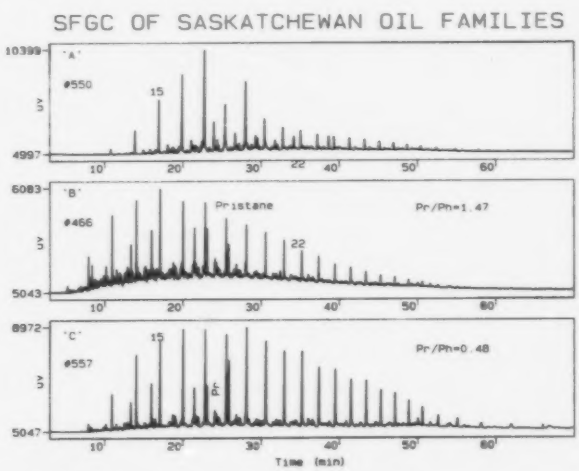


Fig. 3 Saturate fraction gas chromatograms of samples #550, #466, and #557 representing characteristic response of Families A, B and C, respectively.

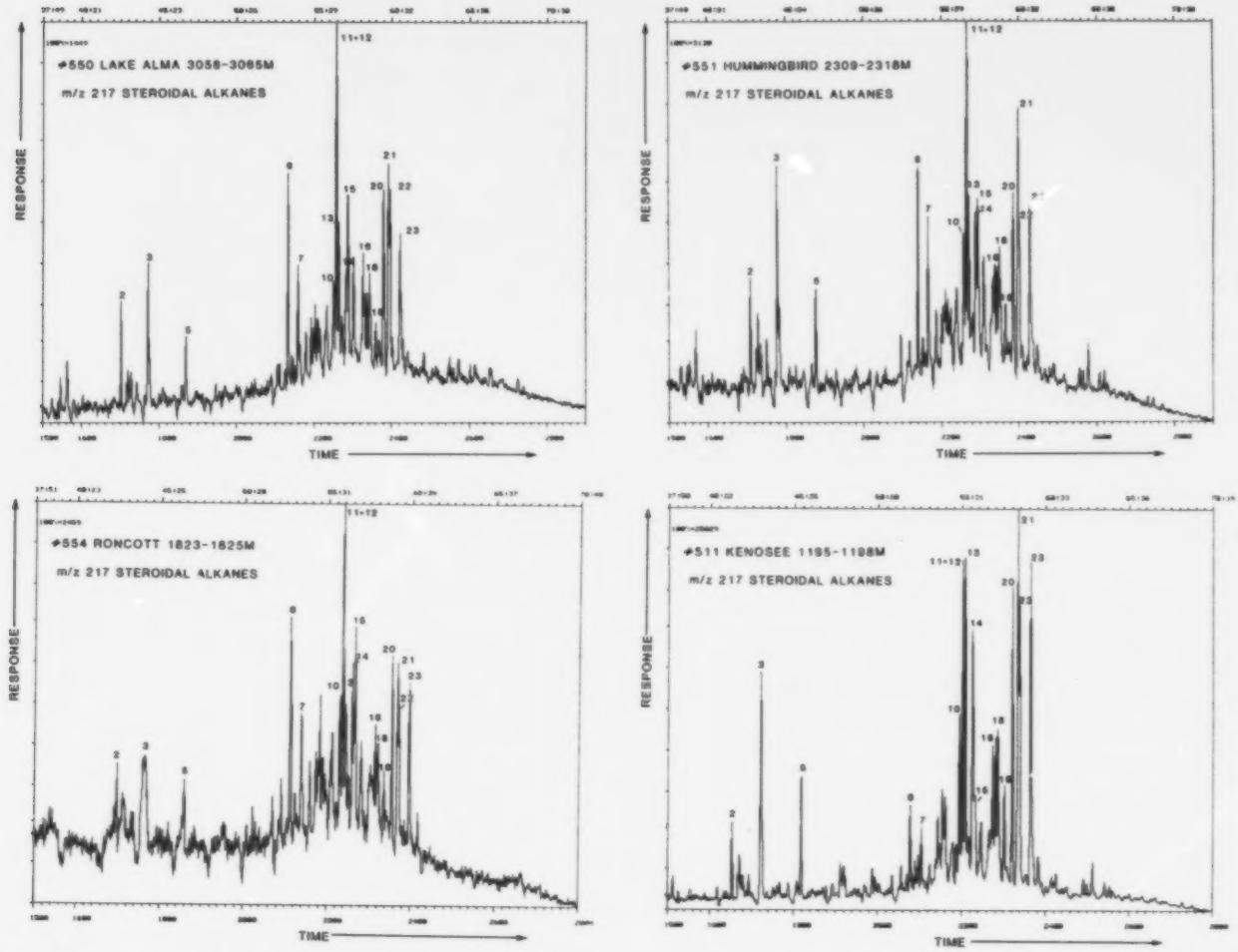


Fig. 4 Mass chromatograms for steroidal alkanes (m/z = 217) by GC - MS analysis of oils characteristic of Family A (#550), Family B(i) (#551), Family B(ii) (#554), and Family C (#511). Peaks identified in these traces are named in Table 4.

Table 4. Peaks identified in m/z 217 traces (see Fig. 4).

2	C_{21} sterane
3	C_{21} sterane
5	C_{22} sterane
6	13β(H), 17α(H)-diacholestane (20S)
7	13β(H), 17α(H)-diacholestane (20R)
10	5α(H), 14α(H), 17α(H)-cholestane (20S)
11	5α(H), 14β(H), 17β(H)-cholestane (20R)
12	24-ethyl-13β(H), 17α(H)-diacholestane (20S)
13	5α(H), 14β(H), 17β(H)-cholestane (20S)
14	5α(H), 14α(H), 17α(H)-cholestane (20R)
15	24-ethyl-13β(H), 17α(H)-diacholestane (20R)
16	24-methyl-5α(H), 14α(H), 17α(H)-cholestane (20S)
17	24-methyl-5α(H), 14β(H), 17β(H)-cholestane (20R)
18	24-methyl-5α(H), 14α(H), 17α(H)-cholestane (20S)
19	24-methyl-5α(H), 14α(H), 17α(H)-cholestane (20R)
20	24-ethyl-5α(H), 14α(H), 17α(H)-cholestane (20S)
21	24-ethyl-5α(H), 14β(H), 17β(H)-cholestane (20R)
22	24-ethyl-5α(H), 14β(H), 17β(H)-cholestane (20S)
23	24-ethyl-5α(H), 14α(H), 17α(H)-cholestane (20R)

Another oil from the same family, #547, is 1.05, and thereby reflects full maturity. Abnormally high values of (20S)/(20R) and β, β/R are observed for oils #550 and #499, members of Families A and B, respectively.

The terpane distributions of the oils in Family A are dominated by the ubiquitous 17α(H)-hopane series of compounds (McKenzie et al., 1984). Compared to the oils in Family C, those of Family A contain very low concentrations

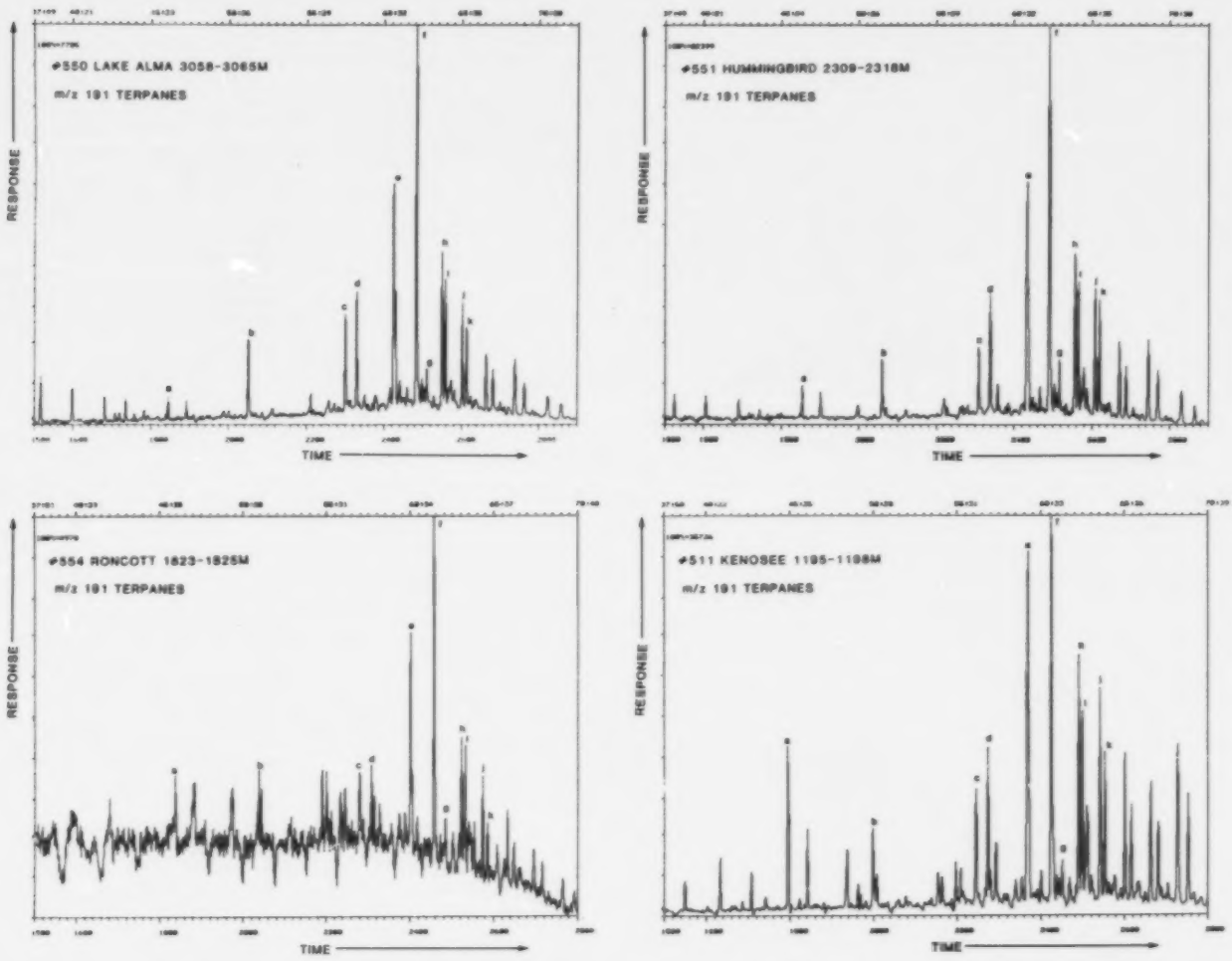


Fig. 5 Mass chromatograms for terpanes (m/z = 191) by GC-MS analysis of oils characteristic of Family A (#550), Family B(i) (#551), Family B(ii) (#554), and Family C) (#511). Peaks identified in these traces are named in Table 5.

Table 5. Peaks identified in m/z 191 terpane traces (see Fig. 4).

a	C_{23} tricyclic terpane
b	C_{24} tetracyclic terpane
c	T_s[18α(H)-trisnorhopane]
d	T_m [17α(H)-trisnorhopane]
e	17α(H)-norhopane
f	17α(H)-hopane
g	moretane
h	(20S)17α(H)-homohopane
i	(20R)17α(H)-homohopane
j	(20S)17α(H)-bishomohopane
k	(20R)17α(H)-bishomohopane

of tricyclic terpanes. The ratio of C_{23} tricyclic/C_{30} hopane is 0.03 for both samples in Family A. Family C oils have ratios of C_{23} tricyclic/C_{30} hopane between 0.31 and 0.49. Within Family B two distinctive groups are recognized on the basis of the C_{23} tricyclic/C_{30} hopane ratios. Group B(i) oils have low C_{23} tricyclic/C_{30} hopane ratios with a range of 0.04 to 0.08, similar to Family A. Group B (ii), have higher C_{23} tricyclic/C_{30} hopane ratios with a range of 0.19 to 0.69, resembling Family C. Family A oils show a major peak in their m/z 191 traces due to the C_{24} tetracyclic terpanes (Aquino Neto et al , 1983).

The families of oils are also reflected by the ratios of C_{29} 17α(H)-norhopane/C_{30} 17α(H)-hopane which we suggest may be sensitive to source rock lithology. Oils from families A and B, excepting sample #499, have values of this ratio less than 0.75. Ratios for oils in Family C are in excess of 0.74, except for sample #548, and commonly in excess of 0.80, with many values exceeding 0.90. Additional features of the oils in Family C include: an enhanced contribution of extended hopanes ($>C_{30}$) on the m/z = 191 chromatograms (Fig. 5) and a predominence of C_{35} hopanes relative to the C_{33} and C_{34} homologues. Oils from Family groups A and B (i) are characterized by a predominence of C_{34} hopanes relative to the C_{33} and C_{35} homologues.

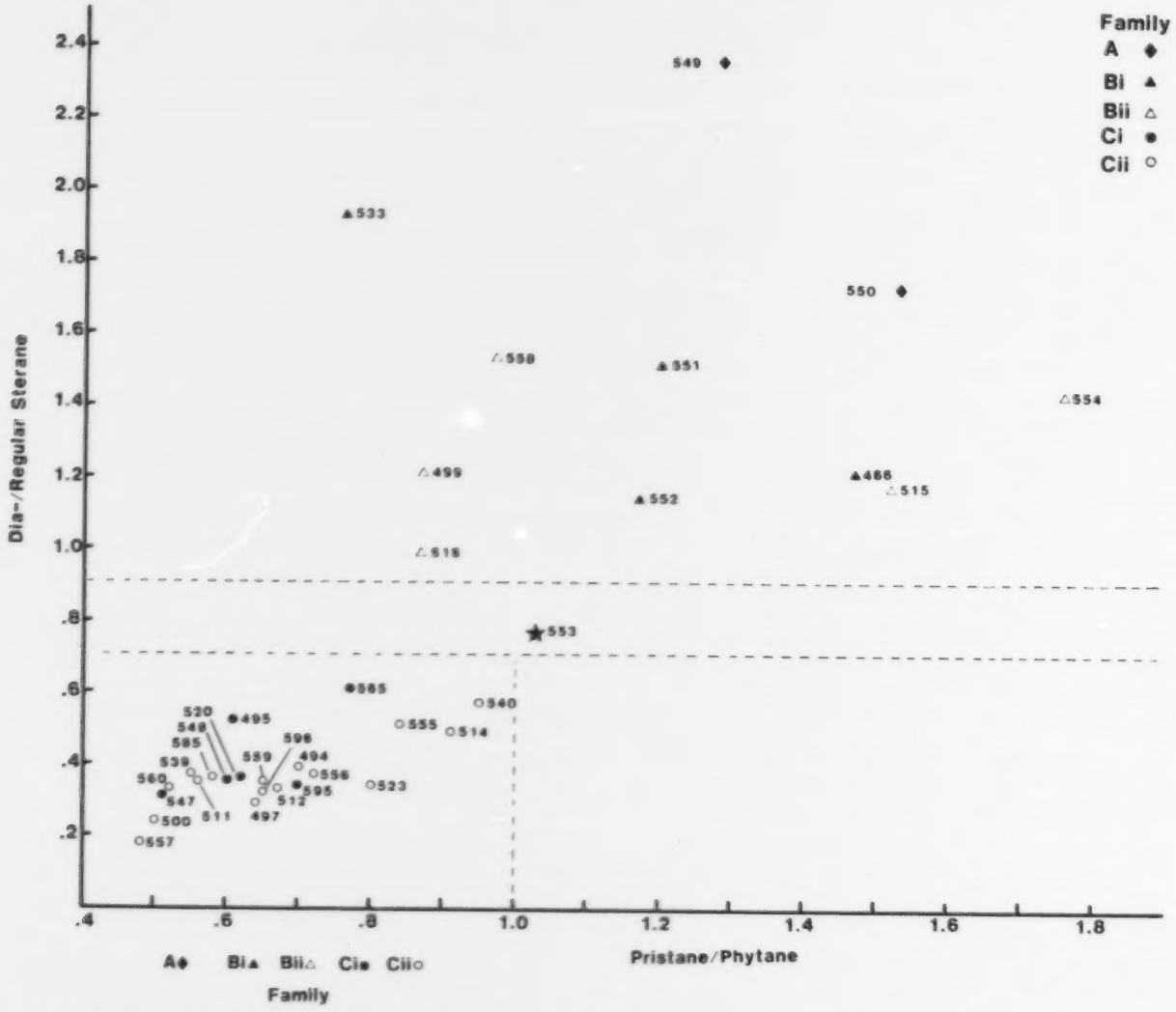


Fig. 6 Cross plot of pristane/phytane ratio against diasterane/regular sterane ratio for oils listed in Table 3. Samples are annotated with respect to families. Sample #553 is believed to be a mix of oils from Families B and C. Critical values for distinguishing families are indicated.

DISCUSSION

CRITERIA FOR THE RECOGNITION OF FAMILIES AND GROUPS OF OILS

The critical criteria for distinguishing the three families of oils from southeastern Saskatchewan are: the ratio of diasteranes/regular steranes which distinguishes Families A and B from C (Table 3; Figs. 4 and 6), and the character of the saturate fraction gas chromatogram to separate Family A from Family B (Fig. 3). Oils fall into two distinct groups based on the abundance of diasteranes. Oils with diasterane/regular sterane ratios greater than 0.9 are distinguished from oils with ratios less than 0.7. Oils with values below these ratios are assigned to Family C. Pristane/phytane ratio generally tends to correlate with the diasterane/regular sterane ratio (Fig. 6). Within the group of oils having diasterane/regular sterane ratios greater than 0.9, there is a considerable range of pristane/phytane ratios, but two distinct families are recognized on the basis of the saturate fraction gas chromatogram. Oils marked by the near absence of pristane and phytane, high abundance of C_{15}, C_{17}, and C_{19} n-alkanes and an even/odd predominance accompanying a low relative abundance of higher homologues ($>nC_{22}$) are assigned to Family A. Oils with abundant pristane and phytane and a greater abundance of higher homologues are assigned to Family B. The distinction between these two families is also observable in the distribution of gasoline range (C_5-C_8) compounds (Snowdon et al, 1987). Oils in Family A tend to be relatively higher in diasterane/regular sterane ratios for a given pristane/phytane ratio and lower in saturate/aromatic ratios, in comparison with Family B oils. Other compositional characteristics conform to these familial groupings. The percentage of asphaltenes is very high in Family A, intermediate in Family C, and low in Family B oils.

It is possible to subdivide the oils in Families B and C. Within Family B, two groups of oils, B(i) and B(ii), are distinguished on the basis of the C_{23} tricyclic/C_{30} hopane ratios (Fig. 7). Group B(i) is low, <0.08, and in this way

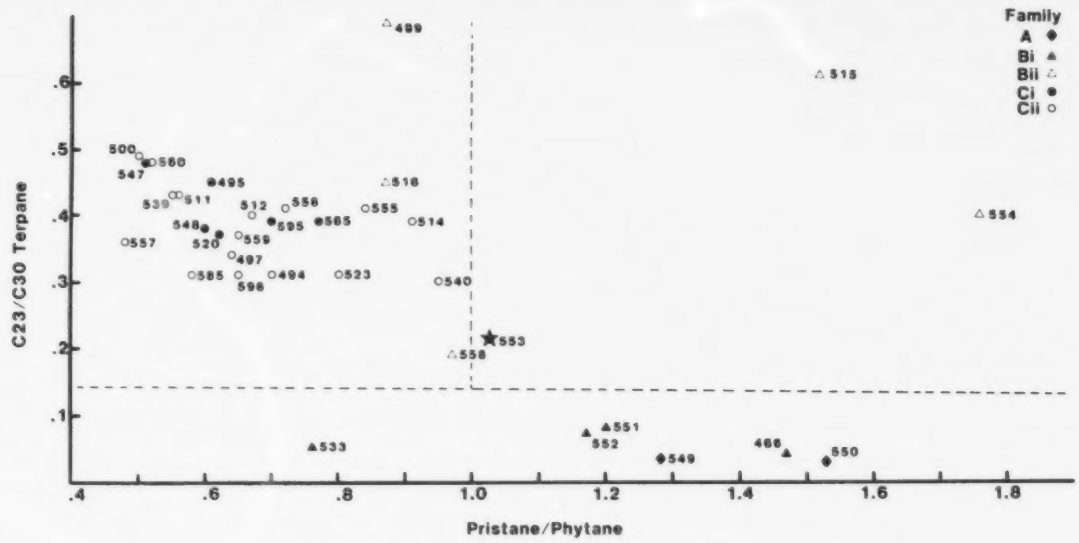


Fig. 7 Cross plot of pristane/phytane ratio against C_{23}/C_{30} terpane ratio. Samples are annotated with respect to families. Critical factors for distinguishing families are indicated.

resembles Family A oils. Group B(ii) ratios are comparable to or greater than oils in Family C. Group B(i) further resemble Family A oils in the predominance of C_{34} hopanes relative to the C_{33} and C_{35} homologues. Two groups of oils are also distinguised within Family C (Fig. 8). Group C (i) is characterized by saturate/aromatic hydrocarbon ratios greater than one, as is the case for all Family B oils, and C(ii) is marked by ratios less than one.

OCCURRENCE OF FAMILIES AND GROUPS

The primary control on the distribution of oils in southeastern Saskatchewan is stratigraphic. Family A oil is identified with the Ordovician Bighorn Group, Family B with Birdbear and Bakken Formations, and the Madison Group, and Family C with the Carboniferous Madison Group and Mesozoic sandstones. There is also an apparent stratigraphic control on the distribution of groups B(i) and B(ii). Group B(i) is present in three pools of the Birdbear Formation and two pools of the Madison Group. Group B (ii) is found in two Bakken Formation pools and the Steelman Midale Beds oil field. Group C (i) is restricted to an elongated area bounded on the west by Range 33W1 and on the east by the border with Manitoba (Fig. 1). Pools with this subfamily of oils occur in the Midale, Frobisher, Alida and Tilston Beds. West and north of this region Group C (ii) oils reside.

One oil, #553, from the Bakken Formation pool in the Hummingbird Field, is intermediate in composition and is inferred to be a mixture of Families B and C (Figs. 5, 6 and 8).

RELATIONSHIP TO PREVIOUS STUDIES

Oils of Family A are similar in composition and stratigraphic distribution to Type I — Group 1 oils of Williams (1974) and Zumberge (1983). The known stratigraphic distribution of these oils is more restricted in Saskatchewan than in North Dakota. Family B and C oils appear to represent oils collectively assigned to Type II — Group 2 oils and the "Bakken-sourced oils" of other investigators (Price et al, 1986a, b, 1984; Leenheer, 1984). This inference is based upon the pristane/phytane abundance and ratios, and the stratigraphic distribution of these oils. The identification of two families of oils in Carboniferous reservoirs has significant implications for the interpretation that a single source rock, the Bakken Formation, has been effective as such.

PATTERNS OF THERMAL MATURITY

A wide range of thermal maturities, as determined from the (20S)/(20R) and β, β/R ratios, are exhibited by the oils in the study area. Oils range from immature, #559, to fully mature #547.

Abnormally high values of (20S)/(20R) and β, β/R are observed for oil #550 (Family A) and #499 (Family B (ii)). This may possibly reflect a certain degree of biodegradation, since it is known that the (20R) isomer is sometimes degraded at a faster rate than other isomers (Volkman et al, 1984; Seifert et al, 1984). However, for these two samples the n-alkane SFGC's are intact. Had biodegradation occurred, the n-alkanes should have been destroyed prior to degradation of the steranes.

With respect to thermal maturity parameters, Ordovician Family A oils are observed or inferred to be fully thermally mature. Deep-lying pools of the upper Paleozoic, such as Roncott and Hummingbird, are also regarded as fully mature. However, in the northeastern portion of the study area, the thermal maturity of oils is the reverse of their stratigraphic position. Oils of progressively lower thermal maturity occur in older reservoir beds. The least mature oil [(20S)/(20R)=.59; β, β/R=.74] is found in the Devonian Birdbear reservoir (Sample #515). Both of these oils are members of Family B. In the same region, oils from Family C at the Mesozoic Wapella (Sample #523) and Red Jacket (Sample #512) fields are significantly more mature than the Family B oils of the underlying Paleozoic reservoirs.

Oils produced from the Carboniferous of the central region of the study, which is demarcated by the subcrop from the Tilston to the Ratcliffe Beds, are comparable in thermal maturity to those of the Mesozoic, although some exceptions exist. These exceptions are restricted to the northwestern side of the study area and include four pools exhibiting oils of

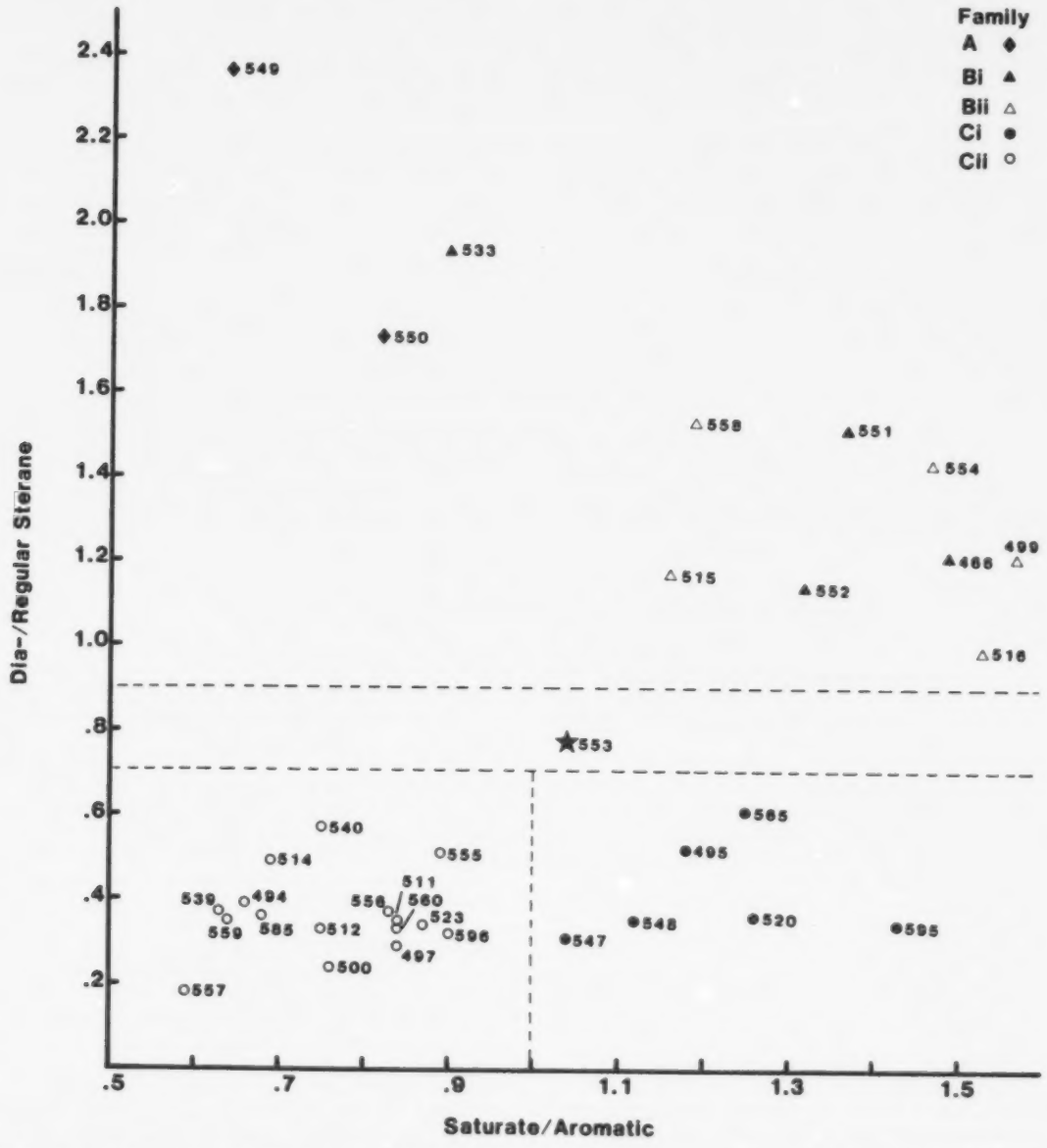


Fig.8 Cross plot of the ratio of saturate/aromatic hydrocarbons against diasterane/regular sterane ratio. Samples are annotated with respect to families. Critical values for distinguishing families are indicated.

slightly lower thermal maturity. These are: North Handsworth (Alida Beds), Viewfield (Frobisher Beds), West Innes (Frobisher Beds) and Benson (Midale Beds).

Along the Oungre-Hummingbird trend, most of the oils exhibit a range of thermal maturities comparable with the oils of the central region. In general their thermal maturity corresponds to stratigraphic position. The oil from the Ordovician at West Oungre is more thermally mature than the Family C oils from Carboniferous in the Oungre trend. However, pools in structural traps at Hummingbird and Lake Alma produce from a variety of stratigraphic levels and yield oils from both families B and C that show no consistent relationship between stratigraphic position and thermal maturity. Anomalous thermal maturity indices in two of the oils having non-biodegraded, n-alkane distributions may represent multiple pulses of migration into the reservoir.

CONSTRAINTS ON SOURCE ROCKS

Each of the three oil families is compositionally distinct and is inferred to be independently sourced.

Oils from Family A are exclusive to Ordovician strata. They are thermally mature and it is inferred that the source is indigenous to the Ordovician System. Carbon number distributions among the steranes indicate that C_{29} are slightly predominant to C_{27}, suggesting a Type II source organic

material (Huang and Meinschein, 1979). A large predominance of C_{29} steranes has been used to indicate a contribution from either algal (Grantham, 1986; Volkman et al, 1981) or higher land plant material (Huang and Meinschein, 1979). The stratigraphic restriction of these oils to Ordovician rocks renders the suggestion of a higher land plant contribution unlikely. The low abundance of long chain n-alkanes ($>nC_{22}$) and the high abundance of the C_{17} and C_{19} compounds is consistent with a primary algal input. Yet, the virtual absence of pristane and phytane, common derivatives from phytol side chains in chlorophyll molecules, indicates a distinctive source kerogen and paleoecology for the precursor organism. This and other compositional peculiarities of Ordovician oils have been recorded by Reed et al (1986) and Fowler et al (1986) who have suggested it indicates a major contribution from simple organisms because of the predominance of *Gloecapsamorpha* prisca in source kerogens.

The high ratio of diasteranes/ regular steranes indicates the presence of clay minerals in the source rock because rearranged steranes in oils are ascribed to clay catalysed rearrangement reactions of precursor sterols, via unsaturated intermediates, to rearrange steranes (Sieskind et al, 1979; Rubinstein et al, 1975).

Two potential Ordovician source rocks have been identified: the shales of the Winnipeg Formation (Osadetz and Snowdon, 1986a; Dow, 1974) and the "kerogenite" beds of the Big Horn Group (Kendall,1976; Kohm and Louden, 1982, 1978). Definitive selection of the effective source awaits further study.

Oils of Family B are restricted to reservoirs from the Birdbear Formation (Upper Devonian) to the Ratcliffe Beds (Carboniferous). These oils, especially group B(i), have some similarities to Family A except that they contain abundant pristane and phytane, and have a lower abundance of asphaltenes and higher ratios of saturate/aromatic hydrocarbons. The pristane/phytane ratio reflects the extent of oxidation of organic debris at and near the sediment-water interface. The diasterane/regular sterane ratio is indicative of clays in the source rock (Rubinstein et al, 1975).

Osadetz and Snowdon (1986a) attributed a limited source rock potential to strata between the Bighorn Group and the Bakken Formation (Devonian and Carboniferous) in part of southern Saskatchewan. Other investigators (Wardlaw and Resinson, 1971) see a significant source potential in the Ratner Member of the Winnipegosis Formation. Other, probably local, potential source rocks have been identified in the Duperow Formation (Osadetz and Snowdon, 1986a), particularly in association with the Flat Lake evaporite member. The distinction between oils of groups B(i) and B(ii) using the ratio of C_{23} tricyclic/C_{30} hopane compounds raises the distinct possibility that the oils of Family B have been derived from more than one source rock, or that the B(i) oils represent a mixture of oils from sources similar to those that gave rise to Family A and Group B (ii) oils. Although the composition and stratigraphic distribution of Family B oils are suggestive of a Bakken source, further correlation of oils in Family B with one or a number of potential sources remains to be determined.

Oils of Family C occur in reservoirs of the Madison Group and Mesozoic reservoirs below the Colorado Group shales. It is significant that oils from this family are not recovered form the Bakken Formation. In contrast to the other two families of oils, Family C is characterized by a low ratio of diasteranes/ regular steranes and low pristane/phytane ratios that are indicative of an insignificant source clay component deposited in an anoxic water column.

Saturate Fraction GC's of extracted hydrocarbons indicate that within the Williston Basin the Bakken Formation shows pristane/phytane ratios greater than one (Leenheer, 1984; Price et al, 1986b, 1984). Furthermore, the stratigraphic distribution of oils in Family C and the low ratio of diasteranes/regular steranes suggest that the argillaceous potential petroleum source rocks of the Bakken Formation have not been the source for Family C oils. Exclusion of the Bakken Formation as a source suggests that Family C oils are indigenous to the Madison Group. Potential petroleum source rocks have been identified in the Lodgepole Formation of the Madison Group (Osadetz and Snowdon, 1986b) although their location lies slightly west of the known pools and not on the generally accepted migration pathways (Price et al . 1984). Detailed descriptions of solvent extracts from the Lodgepole source beds and other similar facies are required before an oil-source correlation can be established.

In contrast with a number of recent investigations, this study suggests that the source of oils for the largest number of pools in southeastern Saskatchewan lies not in the Bakken Formation (Dembicki and Pirkle, 1984; Leenheer, 1984; Price et al, 1984; Webster, 1984; Schmoker and Hester, 1983; Dow, 1974) but within the Madison Group itself. The significance of the geographically limited group of oils C (i), which in gross terms are compositionally similar to oils of Family B, is not understood.

CONSTRAINTS ON MIGRATION

The large gaps in the widespread stratigraphic and geographic distribution of oils in southeastern Saskatchewan suggest that the migration pattern is complex (Fig. 1; Tables 2 and 3). Consideration of the compositional characteristics of the oils and the limited compositional range within a family group suggests that mixing of oils and co-sourcing of pools is not characteristic of this petroleum province. Instead it appears that individual pools have been discretely derived from individual source beds with distinctive compositions. A clear example of this is the Hummingbird Field which produces three distinct oils: from the Ratcliffe Beds (#556, Family C), Bakken Formation (#553, a mix of Families B and C) and Birdbear Formation (#551, Family B (i)), respectively (cf. Brooks et al, 1987). This field is a structural trap controlled by inversion of a multistage salt solution feature following regional salt solution (Smith and Pullen, 1967).

The appearance of oil from different families in a single stratigraphic trend indicates the complex nature of the migration of oils in this basin; in particular, pools producing from the Midale Beds are sealed above and below by the Midale and Frobisher evaporites. Migration into the Midale must have occurred downdip of the underlying Frobisher evaporite. Oils along this trend are of both Families B and (#499) and C(#547, #500, and #514), including C(i) and C(ii). The migration of oils into the Midale Beds appears to have been discrete and selective. A simple model of regional migration from a single source is clearly inadequate.

CONCLUSIONS

1. Three families of oils are recognized within southeastern Saskatchewan. The diagnostic characteristics of each family are the ratio of diasterane/regular sterane and the character of the SFGC. Within two families further subdivisions are recognized on the basis of the ratios of saturate/aromatic hydrocarbons and C_{23} tricyclic/C_{30} hopane ratios.

2. Families of oils are restricted stratigraphically. This allows the inference that two of the Families, A and C, are indigenously sourced by strata in the same stratigraphic Group as the reservoirs that entrap the oil. The source of Family B oils is less well constrained although it too may be stratigraphically close to the reservoirs.

3. The process of migration is poorly understood. It appears that migration into reservoirs was distinct and selective as opposed to widespread and regional.

ACKNOWLEDGEMENTS

The authors appreciate the collection and donation of oils from southeast Saskatchewan for this study by the Saskatchewan Geological Survey, and thank J. E. Christopher and L. K. Kreis for arranging their delivery. This project was set up under the guidance of the O.E.R.D. 6.1.1., Government-Industry Review Committee, and the authors are grateful for this assistance. This work was financially supported by Geological Survey of Canada Projects 780003 and 730062.

REFERENCES CITED

Aquino Neto, F. R., Tendel, J. M., Restle, A., Connan, J. and Albrecht, P. 1983, Occurrences and formation of tricyclic and tetracyclic terpanes on sediments and petroleum. In: Advances in Organic Geochemistry 1981, New York, Wiley and Sons, p. 659-667.

Bailey, N. J. L., Krouse, H. R., Evans, C. R. and Rogers, M. A. 1973, Alteration of crude oil by waters and bacteria — evidence from geochemical and isotope studies; AAPG Bulletin, v. 57, no. 7, p. 1276-1296.

Barchyn, D. 1984, The Waskada lower Amaranth (Spearfish) oil pool, southwestern Manitoba: A model for Spearfish exploration in Saskatchewan; In: Oil and Gas in Saskatchewan, J. A. Lorsong and M. A. Wilson (eds.), Saskatchewan Geological Society, Special Publication Number 7, p. 103-111.

Brooks, P. W., Osadetz, K. G., and Snowdon, L. R. 1987, Origin of compositional differences amongst oils from the Hummingird Field (Paleozoic), southeast Saskatchewan; In: Current Research, Part A, Geological Survey of Canada, Paper 87-1A, p. 331-336.

Dembicki, H., Jr. and Pirkle, R. L. 1985, Regional source rock mapping using a source potential rating index; AAPG Bulletin, v. 69, no. 4, p. 567-581.

Dow, W. G. 1974: Application of oil-correlation and source-rock data to exploration in Williston Basin; AAPG Bulletin, v. 58, no. 7, p. 1253-1262.

Edie, R. W. 1958, Mississippian sedimentation and oilfields in southeastern Saskatchewan; AAPG Bulletin, v. 42, p. 94-126.

Fowler, M. G., Abolins, P., and Douglas, A.G. 1985, Monocyclioalkanes in Ordovician organic matter; In: Advances in Organic Geochemistry, Leythauser, D. and Rullkotter, J. (eds.), Pergamon.

Fuller, J. G. C. M. 1961, Ordovician and contiguous formations in North Dakota, South Dakota, Montana, and Adjoining Areas of Canada and United States; AAPG Bulletin, v. 45, no. 8, p. 1334-1363.

Fuller, J. G. C. M. 1956, Mississippian rocks and oilfields in southeastern Saskatchewan; Saskatchewan Department of Mineral Resources, Report 19, 72 p.

Fuzesy, L. M. 1960, Correlation and subcrops of the Mississippian strata in south-eastern and south-central Saskatchewan; Saskatchewan Department of Mineral Resources, Report 51, 63 p.

Grantham P.J. 1986, The occurrence of unusual C27 and C29 sterane predominances in two types of Oman crude oil. Organic Geochemistry, v. 9., no. 1., p.1-10.

Hartling, A., Brewster, A. and Posehn, G. 1982, The geology and hydrocarbon trapping mechanisms of the Mississippian Oungre Zone (Ratcliffe Beds) of the Williston Basin; In: Proceedings of the fourth international Williston Basin symposium, Regina 1982, J. E. Christopher and J. Kaldi (eds.), Saskatchewan Geological Society - North Dakota Geological Society, p. 217 - 223.

Huang, W. Y. and Meinschein W. G. 1979, Sterols as ecological indicators; Geochimica and Cosmochimica Acta, v. 43, p. 739-745.

Kendall, A. C. 1976, The Ordovician carbonate succession (Big Horn Group) of southeastern Saskatchewan; Saskatchewan Department of Mineral Resources, Report 180, 185 p.

Kent, D. M. 1984, Depositional setting of Mississippian strata in southeastern Saskatchewan: a conceptual model for hydrocarbon accumulation; In: Oil and Gas in Saskatchewan, J. A. Lorsong and M. A. Wilson (eds.), Saskatchewan Geological Society, Special Publication Number 7, p.19-30.

Kohm, J. A. and Louden, R. O. 1978, Ordovician Red River of Eastern Montana and western North Dakota: relationships between lithofacies and production; In: 1978 Williston Basin Symposium — the Economic Geology of the Williston Basin, Proceedings of the Montana Geological Society 24th Annual Conference, Billings Mt., p. 99-117.

Kohm, J. A. and Louden, R. O. 1982, Ordovician Red River of eastern Montana and western North Dakota: Relationships between lithofacies and production; In: Fourth International Williston Basin Symposium Proceedings, J. E. Christopher and J. Kaldi (eds.); Saskatchewan Geological Society, Regina, p. 27-28.

Leenheer, M.J. 1984, Mississippian Bakken and equivalent formations as source rocks in the Western Canadian Basin: Organic Geochemistry, v. 6, p. 521-532.

Mackenzie, A. S., Patience, R. L., Maxwell, J. R., Vandenbrouke, M. and Durand, B. 1980, Molecular parameters of maturation in the Toarcian shales, Paris Basin, France — 1. changes in configuration of acyclic isoprenoid alkanes, steranes and triterpanes; Geochimica and Cosmochimica Acta, v. 44, p. 1709-1721.

McCabe, H. R. 1963, Mississippian oil fields of southwestern Manitoba; Manitoba Department of Mines and Natural Resources, Publication 60-5, 50 p.

Meissner, F. F., Woodward, J., and Clayton, J. L. 1984, Stratigraphic relationships and distribution of source rocks in the greater Rocky Mountain region; In: Hydrocarbon source rocks of the greater Rocky Mountain region, J. Woodward, F. F. Meisner, and J. L. Clayton (eds.); Rocky Mountain Association of Geologists, Denver, p. 1-34.

Osadetz, K. G. and Snowdon, L. R. 1986a, Petroleum source rock reconnaissance of southern Saskatchewan; In: Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p. 609-617.

Osadetz,K. G. and Snowdon, L. R. 1986b, Speculation on the petroleum source rock potential of portions of the Lodgepole Formation (Mississippian) of southern Saskatchewan; In: Current Research, Part B, Geological Survey of Canada, Paper 86-1B, p. 647-651.

Price, L. C., Daws, T. and Pawlewicz, M. 1986a, Organic metamorphism in the Lower Mississippian Reflectance; Journal of Petroleum Geology, v. 9, no. 2, p. 125-162.

Price, L. C., Ging, T., Love, A. and Anders, D. 1986b, Organic metamorphism in the Lower Mississippian - Upper Devonian Bakken shales, Part II: Soxhlet Extraction; Journal of Petroleum Geology, v. 9, no. 3, p. 313-342.

Price, L. C., Ging, T., Daws, T., Love A., Pawlewicz, M. and Anders, D. 1984, Organic metamorphism in the Mississippian-Devonian Bakken shale, North Dakota portion of the Williston Basin; In: Hydrocarbon source rocks of the Greater Rocky Mountain region, Woodward, J., F. F. Meissner and J. L. Clayton (eds.); Rocky Mountain Association of Geologists, Denver, p. 83-134.

Reed, J. D., Illich, H. A. and Horsfield, B. 1986, Biochemical evolutionary significance of Ordovician oils and their sources; Organic Geochemistry, v. 10, p.347-358.

Rubinstein, I., Sieskind, O. and Albrecht, P. 1975, Rearranged sterenes in a shale: occurrence of simulated formation; Journal of the Chemical Society, Perkin Transactions I, p. 1833-1835.

Saskatchewan Energy and Mines 1984, Reservoir Annual 1983; Saskatchewan Energy and Mines, Petroleum and Natural Gas, Miscellaneous Report 84-1.

Schooker, J. W. and Hester, T. C. 1983, Organic carbon in the Bakken Formation United States portion of Williston Basin, AAPG Bulletin, v. 67/12, p. 2165-2174.

Seifert, W. K., Moldowan, M. J. and Demaison, G. J. 1984, Source correlation of biodegraded oils; Organic Geochemistry, v. 6, p. 633-643.

Sieskind, O., Joly, G. and Albrecht, P. 1979, Simulation of the geochemical transformation of sterols: superacid effect of clay minerals; Geochimica and Cosmochimica Acta, v. 43, p. 1675-1679.

Smith, D. G. and Pullen, J. R. 1967, Hummingbird structure of southeast Saskatchewan; Bulletin of Canadian Petroleum Geology, v. 15, no. 4, p. 468-482.

Snowdon, L. R. 1978, Organic geochemistry of the Upper Cretaceous/Tertiary delta complexes of the Beaufort Mackenzie Sedimentary Basin; Geological Survey of Canada, Bulletin 291.

Snowdon, L. R., Osadetz, K. G., and Brooks, P. W. 1987, Analysis of gasoline range hydrocarbons in southern Saskatchewan (abstract); In: Program with Abstracts, v. 12, Geological Association of Canada - Mineralogical Association of Canada, Saskatoon 1987.

Van Delinder, D. G. 1984, Source of oils in Cretaceous fields of Southern Saskatchewan; In: Oil and Gas in Saskatchewan, J. A. Lorsong and M. A. Wilson (eds.), Saskatchewan Geological Society, Special Publication Number 7, p. 113-118.

Volkman, J. K., Alexander, R., Kagi, R. I. and Rowlard, S. J. 1984, Biodegradation of aromatic hydrocarbons in crude oils from the Barrow sub-basin of western Australia; Organic Geochemistry, v. 6, p. 619-632.

Volkman, J. K., Gillan, F. T., Johns, R. B. and Eglinton, G. 1981, Sources of neutral lipids in a temperate intertidal sediment; Geochimica et Cosmochimica Acta, v. 43, p. 1675-1679.

Wardlaw, N. C. and Resinson, G. E. 1971, Carbonate and evaporite deposition and diagenesis, Middle Devonian Winnipegosis and Prairie evaporite of south-central Saskatchewan; AAPG Bulletin, v. 55, p. 1759-1786.

Webster, R. L. 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota; In: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region, Woodward, J., Meissner, F. F. and Clayton, J. L. (eds.), Rocky Mountain Association of Geologists, Denver, p. 57-81.

Williams, J. A. 1974, Characterization of oil types in Williston Basin; AAPG Bulletin, v. 58, no. 7, p. 1243-1252.

Zumberge, J. E. 1983, Tricyclic diterpane distributions in the correlation of Paleozoic crude oils from the Williston Basin; In: Advances in Organic Geochemistry 1981, John Wiley & Sons Ltd., p. 738-745.

A STRATIGRAPHIC TEST OF GYPSUM DEHYDRATION AND IMPLICATIONS FOR BASIN DEVELOPMENT

CAROL KINDLE LEE ROARK AND TERESA E. JORDAN

Cornell University,
Ithaca, New York

The Williston Basin was the site of gypsum deposition throughout its Paleozoic history. The economic significance of dehydrated gypsum, or anhydrite, as a trap and environmental indicator is well documented. Our work concerning gypsum dehydration indicates that the presence of gypsum/anhydrite also has important consequences for the stratigraphic, geochemical and subsidence history of the basin.

Laboratory results indicate that gypsum ($CaSO_4.2H_2O$) is the calcium sulfate phase at equilibrium with water at surface temperatures and pressures, and moderately high salinities. Increasing pressure and temperature, analogous to burial, cause dehydration of gypsum to form anhydrite ($CaSO_4$) in the subsurface. Under open system conditions, in which the water of crystallization removed from the gypsum molecular structure can be driven off, the gypsum-anhydrite phase change is accompanied by a 38 per cent volume decrease, or 29 per cent density increase. The preservation of gypsum pseudomorphs, however, suggests that the gypsum-anhydrite transition may be accompanied by influx of sulfate-rich basinal water and in situ deposition of additional anhydrite, in which case the molecular scale volume change would not be seen on the scale of a sedimentary section.

We have devised a quantitative test for evidence of this predicted large-scale volume change which employs differential compaction evidence from the sedimentary record; the approach is analogous to studies of carbonate differential compaction. The test is based upon the theory that (1) if two horizons can be identified as near-horizontal datums and (2) if input data points are chosen such that differences in the tectonic subsidence, eustatic and isostatic factors of sedimentary accumulation between the two points are negligible, then sedimentary thicknesses of the two sections should be equal. If they are not equal and the above-stated conditions have been met, the remaining differences in sedimentary thicknesses must be due to differential burial-related volume changes. Since compaction of non-calcium sulfate lithologies has been quantitatively described by other researchers, the unknown calcium sulfate burial-related volume changes which represent the gypsum-anhydrite transition can be calculated.

Middle Devonian strata of the southeastern (North Dakota) portion of the Williston Basin provide the unique sedimentary circumstances necessary for this quantitative test for large-scale volume changes associated with the gypsum-anhydrite transition. The top of the Ashern Formation/base of the Winnipegosis Formation provides the lower near-horizontal datum. Differentiation of basinal carbonate mound and deep basin depositional environments created significant depositional topography in the upper Winnipegosis Formation, over which evaporites of the overlying Prairie Formation were deposited. This stratigraphic combination allows comparison of closely-spaced sedimentary sections (a) containing relatively thick, originally gypsum strata with sedimentary sections (b) containing little or no calcium sulfate. The top of the Second Red Bed Member of the Dawson Bay Formation is used as the upper near-horizontal datum, bounding the test stratigraphic interval.

The value derived from our Williston Basin Middle Devonian test for the change in volume associated with the gypsum-anhydrite transition is 37 per cent with standard deviation of 4 per cent. This confirms that there is a volume reduction during the conversion of original gypsum to anhydrite which is of a scale that is significant in the history of a sedimentary section. Implications of the volume loss can be immediately incorporated into stratigraphic and geochemical models for hydrocarbon and mineral exploration. The volume change should also be considered in studies of basin mechanisms to remove apparent episodicity and to avoid error in calculations of tectonic subsidence.

SALINITY, OXYGENATION, AND TOPOGRAPHIC CONTROLS ON MISSISSIPPIAN SUBTIDAL SEDIMENTATION IN A PORTION OF THE MISSION CANYON FORMATION, WILLISTON BASIN, NORTH DAKOTA

HOWARD J. FISCHER, MARK R. LUTHER, KURT E. EYLANDS AND CHRISTOPHER F. QUINN

Department of Geology and Geological Engineering,
University of North Dakota
Grand Forks ND 58202

Our model for the deposition of sublittoral rocks from the Mississippian Mission Canyon Formation is derived from the examination of cores and wireline logs from hydrocarbon-producing fields in Billings County and the Bottineau-Renville County area of North Dakota. During the past four years, seven Master of Science theses at the University of North Dakota have focused on the deposition and diagenesis of the Mission Canyon Formation. In addition to the contributions by the writers of this report, information collected in those studies has been helpful in developing this model. The ideas presented herein are therefore somewhat preliminary, and represent our present understanding of the Mission Canyon depositional setting. An earlier version of the model was presented by Fischer et al (1986).

The model outlined in this report calls for salinity to be the major factor controlling sedimentation patterns throughout "Mission Canyon time". The carbonate section developed in response to a general increase in salinity through time that was punctuated by rapid, periodic fluctuations in salinity that controlled lithofacies distribution within the carbonate succession. Local changes in salinity, sedimentation rate, oxygenation above and below the sediment-water interface, and bottom topography accentuated the effects of the broad salinity changes and controlled the local variations in lithologies, organism distribution, sedimentary structures, and evaporite mineral distribution within the Mission Canyon section.

The majority of the Mission Canyon carbonates from Billings, Bottineau, and Renville Counties show characteristics that suggest formation in a shallow sublittoral setting. The rocks from Billings County are mainly mudstones and wackestones containing the remains of a relatively low-diversity epifauna of both stenohaline and euryhaline organisms, low numbers of stenohaline forms, a low to moderately oxygen tolerant infauna, and abundant organic material. Local accumulations of echinoderms and corals in packstone textures are also found. The rocks in Billings County are extensively dolomitized and contain a littoral facies and abundant evaporite minerals at the top of the section (Stephens, 1986; Fischer et al, 1986)

Rocks in Bottineau and Renville Counties contain lithologies similar to those in Billings County, although inorganic allochems and particularly coated grains are more common. Increasing amounts of evaporite minerals and littoral sediments are also found upward in the section (Quinn, 1986, Luther and Quinn, 1985).

In epeiric seas, bottom waters may become more saline through time as evaporation, particularly at the margin of the sea, produces seaward-flowing, bottom-hugging brines of elevated salinity (Scruton, 1953). It has been demonstrated that as salinity increases in marine water, the ability of the water column to contain dissolved oxygen decreases (Kinsman et al, 1974). Thus bottom waters, in addition to becoming brines, may also contain low concentration of dissolved oxygen.

The brines, being more dense than the remainder of the water column, would have accumulated on the sea bottom and flowed away from the sea margin due to a difference in head between the brine (greater head) and less saline water in the seaward direction. Closed topographic lows on the sea floor would have retained the brines, while linear lows, elongated in the flow direction may have acted as conduits for the movement of the brines seaward. In addition, the lack of oxygen in the topographic lows would retard the growth of carbonate-shelled epifauna, and produce a mudstone texture with very few fossil allochems. Lack of oxygen would also produce a sediment with abundant preserved organic material and an ichnofauna indicating low levels of oxygen below the sediment-water interface (Byers, 1977).

The drag on seaward moving brines caused by friction with the sea bottom and overlying, shoreward-moving, fresher marine waters, would have been capable of forming a dynamic barrier to circulation within the sea. The barrier would have restricted the free exchange of water from more open marine environments with the more stagnant, interior and shoreline waters (Scruton, 1953). This dynamic barrier would also have barred the outward flow of the brines until a reduction in drag, caused by reduced inflow of overlying, shoreward-moving waters or increased head of the accumulating brines allowed the dynamic barrier to collapse periodically and the bottom brines to flow seaward.

The elevated salinity created throughout the sea by these processes is the major controlling factor in the chemical and biological evolution of Mission Canyon lithofacies. Reduced levels of oxygen, coupled with elevated salinities, easily explains the lower levels of productivity (numbers of organisms) of such stenohaline groups as the brachiopods, bryozoans, trilobites and in many places the corals and echinoderms. Where euryhaline forms such as green algae and ostracods are found they occur in higher, but still not excessive, numbers.

Increased salinity and decreased oxygenation also explain the low diversity found within taxa in the Billings County area. In both stenohaline and euryhaline groups, the numbers of taxa are lower than those found in sections from more open marine environments. In addition, a succession of ichnofacies, preserved mainly in topographic lows and adjacent flat areas of the bottom, indicates variable, low to moderate levels of oxygenation in the bottom sediments and the water column (Fischer et al, 1986). The predominantly dark-colored, organic-rich rocks that comprise the majority of the Mission Canyon succession in Billings County confirm that low oxygen levels

(reducing conditions) existed within the accumulating sediments. Since much of the section in the Billings Anticline area is rich in carbonate mud, with only local concentrations of bioclasts, and because of the evolving chemical composition of the water column, it is reasonable to suggest that the majority of the carbonate mud in that area was produced by inorganic precipitation.

A factor that must be addressed in evaluating sedimentation rates, biodiversity and population density is the affect of compaction on the section. With the abundance of stylolites and mechanical compaction features found in the Mission Canyon succession representing thickness reduction and packing enhancement, it is likely that in many cases, allochems within the compacted rocks are closer together and therefore appear more abundant than they were during deposition. In the same way, the total sediment thickness is reduced, and any attempt to evaluate sedimentation rates must be modified to account for the effects of compaction. For the sake of simplicity, in trying to remove the influence of compaction, we have doubled the thickness of the section. We have also modified the apparent packing by suggesting that in many cases, packstones have been compacted from wackestones and wackestones have been compacted from mudstones. This significantly modifies the interpretations that can be drawn from the rocks now preserved. If the fossil content of a wackestone is reduced to that of a mudstone, and the number of organisms preserved in a packstone is reduced to that of a wackestone, then the biological productivity of the area is seen to have been much lower than that determined from examining the compacted rocks. Thus, only rarely were there enough organisms present to accumulate in a wackestone, much less a packstone texture. The uncompacted sediment pile may have been at least 1500 feet (457 metres) thick by this reasoning. If a value of seven million years is assumed for the duration of Mission Canyon sedimentation, we can derive a maximum sedimentation rate of 0.21 feet (0.06 metres) per thousand years. This is a slow rate for any marine environment, especially when compared with rates of sedimentation in modern areas of carbonate production.

This model explains the formation of the sublittoral portion of the existing Mission Canyon stratigraphic succession by a combination of variations in salinity, oxygenation, and topography. Interactions between the evolving marine water, developing brines, brine movement, and the biological and chemical components in the various depositional environments can account for the entire preserved sediment package. Therefore, rather than calling on a physical barrier to account for the restricted conditions that produced some of the lithologies developed across the area, the lateral, "band-like" distribution of the facies is explained by bodies of water with different salinities and oxygen values forming across the study area. Since salinity gradients would be established away from the margin of the epeiric sea, concentric bands of progressively less saline water would develop from Bottineau (shoreward) to Billings County (seaward). The lateral migration of the salinity bands would cause the vertical stacking of sediments showing different degrees of restriction as a particular chemical environment caused a specific lithofacies to form in a given area.

Episodic changes in levels of salinity and oxygenation in the water covering the study area, possibly caused by the periodic flow of brines in response to the collapse of a dynamic circulation barrier, would therefore cause the lateral distribution and vertical succession of the facies. In addition, topography, brine movement or concentration, and oxygenation would become important local controls on sublittoral sedimentation.

REFERENCES CITED

Byers, C. W., 1977, Biofacies patterns in euxinic basins: a general model; In: Cook, H.E., and Enos, P. (eds.), Deep-water carbonate environments, Society of Economic Paleontologists and Mineralogists Special Publication No. 25, p. 5-17.

Fischer, H. J., Stephens, R. A., and Valvik, J.R., 1986, Topographically controlled carbonate facies in Mississippian epeiric sea deposits; Williston Basin, North Dakota, Geol. Society of America Abstracts with Programs, Vol. 18, p. 602.

Kinsman, D. J. J., Boardman, M., and Borcsik, M., 1974, An experimental determination of the solubility of oxygen in marine brines; In: Coogan, A. H. (ed.), Fourth Symposium on Salt: Northern Ohio Geological Society, Cleveland, OH, Vol. 1, p. 325-327.

Luther, M.R., and Quinn, C. F., 1985, Upper Mississippian hydrocarbon producing zones of the Wiley, Chola, Lake Darling, and Donnybrook Fields, NE Williston Basin, North Dakota: Society of Economic Paleontologists and Mineralogists Annual Midyear Meeting Abstracts, Vol. 2, p. 57.

Quinn, C. F., 1986, Depositional history and diagenesis for the Sherwood and Bluell beds (Mississippian), southwestern Renville County, North Dakota: Unpublished M.Sc. Thesis, University of North Dakota, 254 p.

Scruton, P. C., 1953, Deposition of evaporites: American Assoc. of Petroleum Geologists Bulletin, Vol. 37, p. 2498-2512.

Stephens, R. A., 1986, Depositional history and diagenesis of the upper Mission Canyon and lower Charles Formations (Mississippian), Billings County, North Dakota; Unpublished M.Sc. Thesis, University of North Dakota, 236 p.

SEDIMENTARY AND DIAGENETIC CONTROLS ON RESERVOIR PROPERTIES: MIDALE FIELD, SOUTHEASTERN SASKATCHEWAN

JOHN KALDI*

J. Kaldi Consulting
436 - 34th Avenue N.W.
Calgary, Alberta, Canada
T2K 0B8

The Midale Field is one of several oil fields producing from the Mississippian Midale Beds of southeastern Saskatchewan. The "Midale Trend" comprises a series of subcrop-parallel stratigraphic traps that extend NW-SE to the U.S. border. Many of these fields have been on production since the 1950s and are now prime candidates for various types of enhanced recovery schemes. For this reason geological investigations have been directed towards detailed characterization of the reservoir units.

The reservoir units at the Midale Field consist of the lower, middle and upper zone carbonates of the Midale Beds, sandwiched between impermeable subtidal anhydrites of the Frobisher Evaporite below, and supratidal anhydrites of the Midale Evaporite above. Lower zone carbonates consist of packstones to wackestones that contain up to 60 per cent replacive anhydrite. This anhydrite commonly contains hydrocarbon inclusions, suggesting either coeval emplacement or anhydrite later than hydrocarbon. Additional two-phase fluid inclusions within the anhydrite suggest maximum temperatures of crystallization of 115-130°C, conditions probably not attained until Cretaceous times. Local dissolution of these relatively late-state anhydrites produces a vugular texture.

Middle zone carbonates vary across the field, comprising 5 possible facies. These are:

(i) oolitic grainstone shoals,
(ii) crinoidal grainstone shoals,
(iii) intershoal mudstones and wackestones,
(iv) partially dolomitized wackestone to packstone matrix, and
(v) wholly dolomitized wackestone to packstone flanking beds.

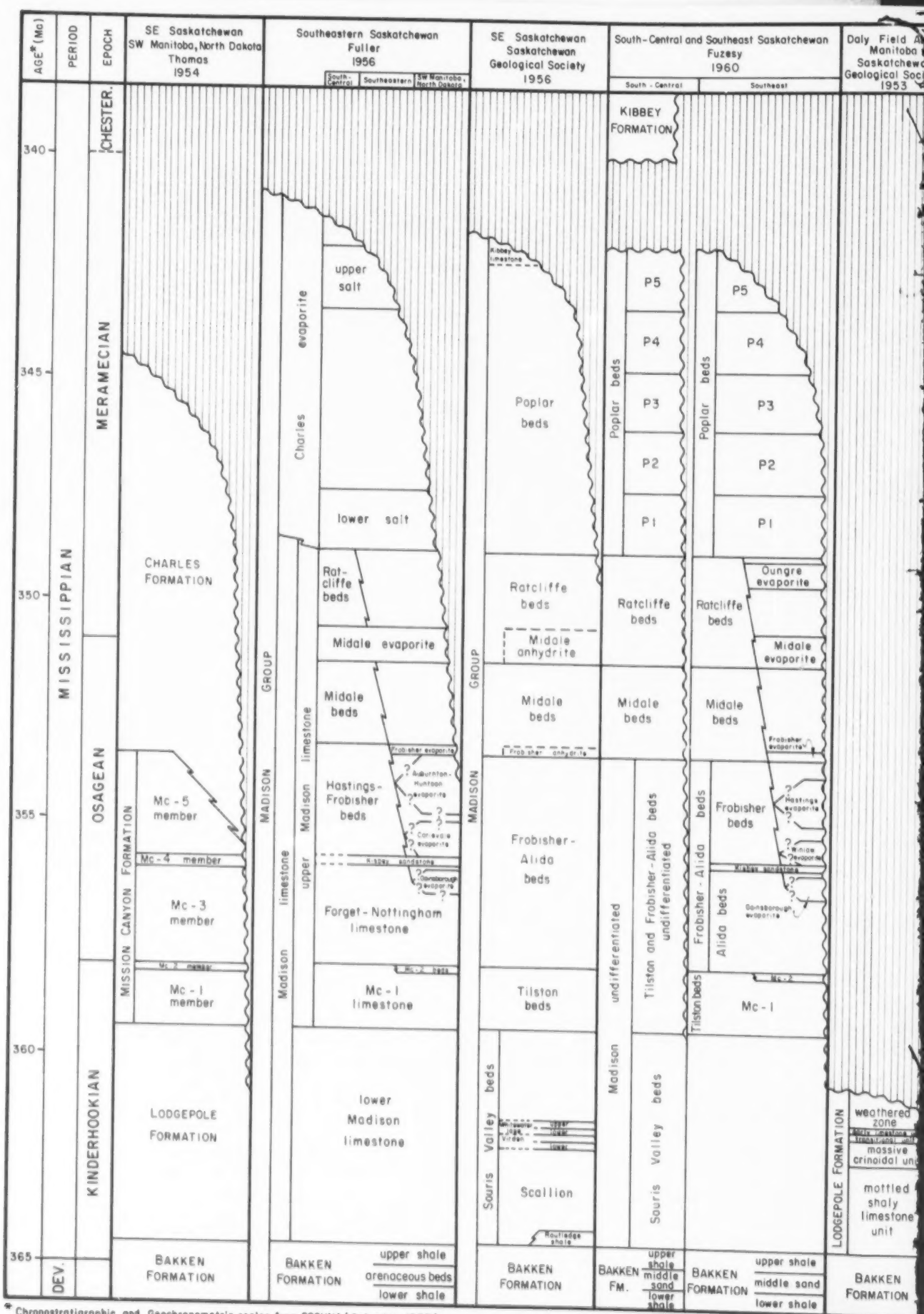
Shoal facies (i and ii) are generally non-viable economic targets due to cementation by block calcite cements in ooid shoals and syntaxial cements in crinoid shoals. Both cements are non- to blotchy luminescent, and have stable isotopic signatures consistent with formation from marine or near marine meteoric fluids. Intershoal facies (iii) formed in paleotopographic lows and contain low porosity, low permeability argillaceous lime mudstones and wackestones. The best reservoir potential is found in the two facies occupying the broad flanks of both ooid and crinoid shoals: Partially dolomitized facies (iv) consist of calcite allochems set in a dolomite matrix. Production is mainly from intercrystalline pores of the matrix, with porosity averaging 15 per cent and permeability 0.75 md. Wholly dolomitized facies (v) owe their origin to further diagenetic alteration of the partially dolomitized rocks. Calcite allochems of this facies were leached by aggressive meteoric fluids introduced during the post-Mississippian — pre-Mesozoic hiatus. These fluids were concentrated near impermeable rocks. Hence, this facies occurs preferentially above and downdip of cemented crinoid shoals, has porosities that are generally 18 per cent or higher, and permeabilities on the order of a millidarcy.

FACIES	REC. EFFIC.	ϕ	K-max	ASP. RAT	COORD. NUM.
Upper Zone	0.50	.16	4.11	2.67	5.25
Shoals (i, ii)	0.19	.03	0.03	---	2.25
Intershoal (iii)	0.28	.06	0.25	0.37	2.80
Matrix (iv)	0.49	.15	0.75	1.77	3.89
Wholly Dol. (v)	0.51	.18	0.97	4.11	7.21
Lower Zone	0.45	.12	2.92	14.25	8.22

Upper zone carbonates are uniformly microcrystalline dolomites and dolomitic limestones. The main pore type is a non-fabric-selective oblique to vertical microfracture system which results in porosities of 9-20 per cent and permeabilities of several to tens of millidarcies. Stable isotopes suggest that dolomitization was a continuous process, starting with dolomitizing evaporitic brines ($\delta^{18}O_{PDB}$ +2 to+4) that evolved to mixed meteoric fluids ($\delta^{18}O_{PDB}$ -2 to -5).

Characterization of the Midale Field involves relating sedimentological and diagenetic parameters described above to quantifiable rock properties such as porosity/permeability, recovery efficiency and pore geometric properties (e.g. aspect ratios and coordination numbers).

* Present address: ARCO, Room G132, 2300 West Plano Parkway, Plano, Texas 75075



* Chronostratigraphic and Geochronometric scales from COSUNA (Salvador , 1985)

Fig. 2 - Nomenclature chart of the Mississippian Madison Group. Lithostratigraphic units formally defined as in the North American Stratigraphic Code are shown in upper case letters. The age assigni
Special Publication No. 9, 1987.

SE Saskatchewan
Saskatchewan Geological Society
1956

South-Central and Southeast Saskatchewan
Fuzesy
1960

Daly Field Area, Manitoba
Saskatchewan Geological Society
1953

Virden-Whitewater Lake Area
Manitoba
Stanton
1955

Daly Field Area, Southeastern Manitoba
Organ & Russin
1956

Southwestern Manitoba
McCabe
1959, 1963

North-Central, North Dakota
SW Manitoba, SE Saskatchewan
Harrison & Flood
1956

Bottineau County, North Dakota
Anderson & Nelson
1956

North Dakota
Anderson
1958

Williston Basin
Smith
1960

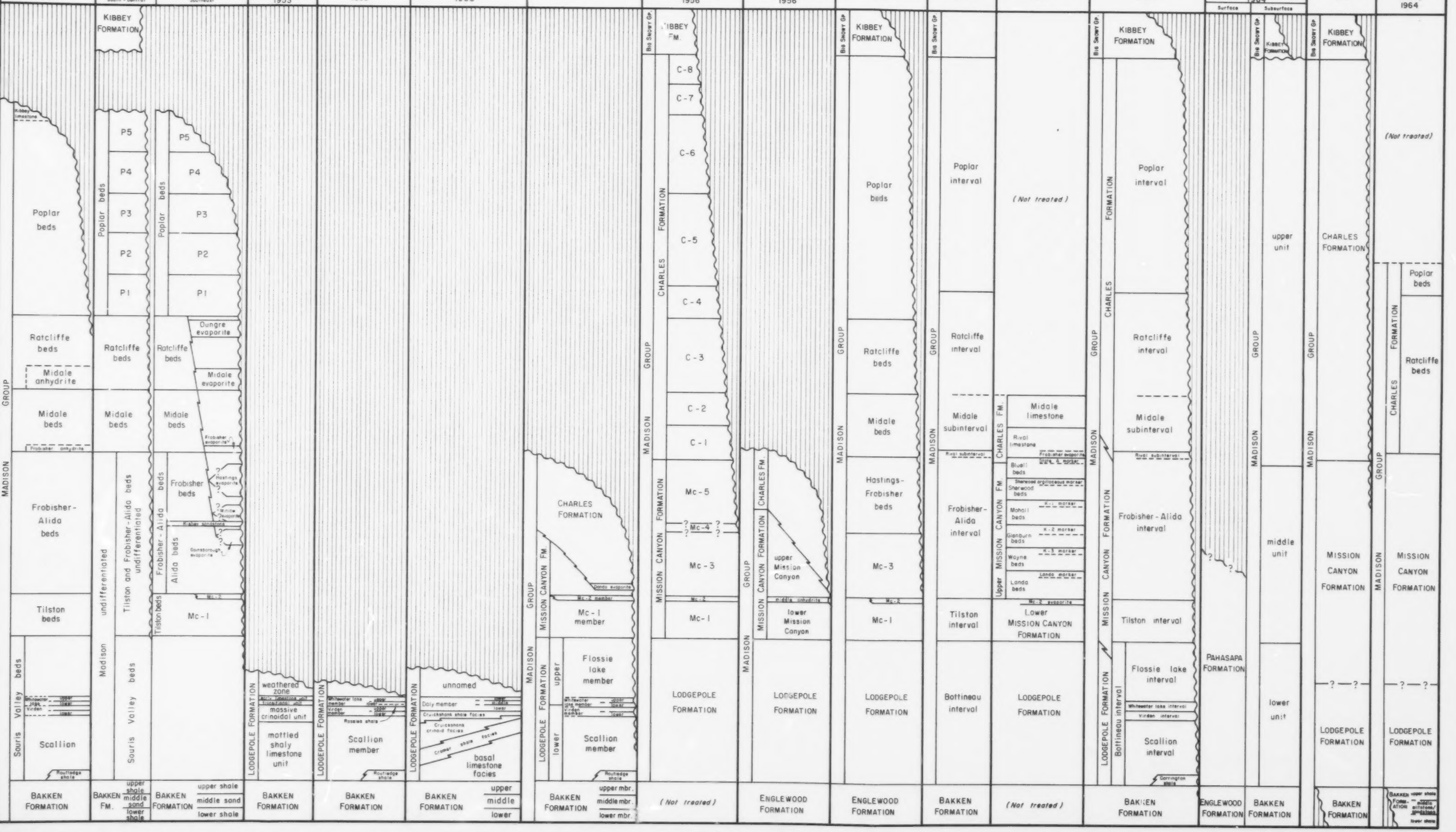
North-Central, North Dakota
Harris, Land, & McKeever
1966

North Dakota
Bluemle, Anderson, & Carlson
1980

Western South Dakota and Adjoining Areas
Gries & Mickelson
1964

Northern Montana
Nordquist
1953

Eastern Montana
Billings Geological Society
1964



efined as in the North American Stratigraphic Code are shown in upper case letters. The age assignments are approximate. The interpretation of the age assignments was made following Peterson (1984). This figure accompanies the paper "The Madison, a nomenclatural review with a look to the future" by C.G. Carlson and J.A. LeFever; In: Carlson, C.G., and Christopher, J.E., eds., Fifth International Williston Basin Symposium, Saskatchewan Geological Society